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Clean, Sustainable, Responsible: Nuclear Power for the U.S.

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A call for action to provide clean energy for the U.S. from a group of scientists from Boston University, Harvard University, and MIT – a non-technical assessment for the concerned citizen.

Nuclear Power is the most practical, sustainable, and environmentally friendly energy generation option available to the United States in the near future. It is "green,"—it does not endanger the environment. It is sustainable—enough fuel to meet U.S. needs for well over a hundred years is readily available. With further technical developments, nuclear power can become "renewable." It is safe.

Yet for many the idea of Nuclear Power is politically unsavory and upsetting—it is associated with negative events and disturbing images: the incidents at Chernobyl and Three-Mile-Island and the terror of nuclear warfare.

In this narrative, we define the energy problems that the U.S. currently faces, carry out an analysis of options, and present the conclusion that nuclear power must play a major role in meeting U.S. energy needs for at least the next half century. Finally, we provide a counterpoint to common objections raised in opposition to the use of Nuclear Power.

History of Energy

Throughout U.S. history, a cheap, plentiful energy supply has been the driving force behind the technological innovations that improved our quality of life.

In the early years of the industrial revolution, water and wood energy provided the power for technological advances. In the nineteenth century, coal superseded wood. In the twentieth and twenty-first century, oil and natural gas became the primary power source.

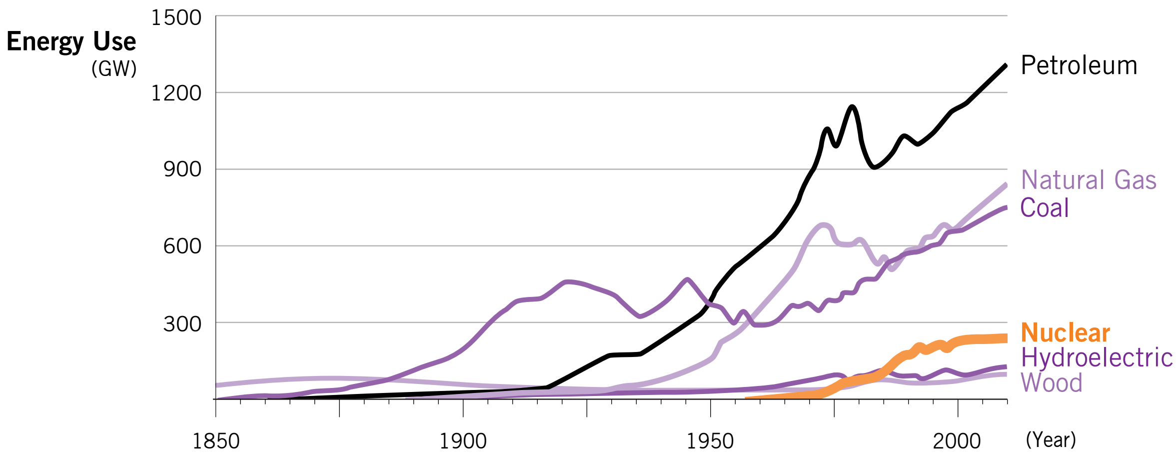


Figure 1: **History of U.S. energy sources and their primary energy output**

Today's Twin Problems: Environment and Energy Security

Energy-rich fossil fuels are no longer a desirable source of power: **obtaining oil is increasingly risky and difficult, and we are significantly altering the atmosphere of our planet Earth through the effects of CO_2 pollution caused by burning of fossil fuels.**

We have known for decades that our survival depends on finding new sources of energy. Yet we import more oil today than ever before. …The only way this century will be another American century is if we confront, at last, the price of our dependence on oil.

—U.S. President Barack Obama, State of the Union, 2009

In the last two decades, the U.S. has been involved in two wars in the Middle East, where the world's major source of oil is located. Until the U.S. dependence on foreign oil is significantly reduced, there is every expectation that increasing amounts of our economic, political, and military power will be expended in the name of energy security.

Even if obtaining fossil fuels was not an issue, it would remain a problematic power source for environmental reasons.

The waste produced by burning fossil fuels includes greenhouse gases like carbon dioxide (CO_2) and methane, which have accumulated in the Earth's atmosphere over the last 200 years. Currently, carbon dioxide presence in the Earth's atmosphere is estimated at 385 parts per million—the highest value in the last half-million years and far above the 260–280 parts per million prior to industrialization. Basic scientific arguments suggest that the increased CO_2 levels will heat the Earth, and measurements indicate that the average temperature at the Earth's surface has significantly risen over the last 100 years.

It is not acceptable, nor is it possible, for the U.S. to continue to burn fossil fuels indefinitely at present levels and without capturing and storing CO_2, thereby putting in clear jeopardy the planet on which we have evolved.

The Size of the Problem

The three main sources of CO_2 emissions in the U.S. are power stations (coal), transportation (oil), and industrial, commercial, and residential use (oil and gas):

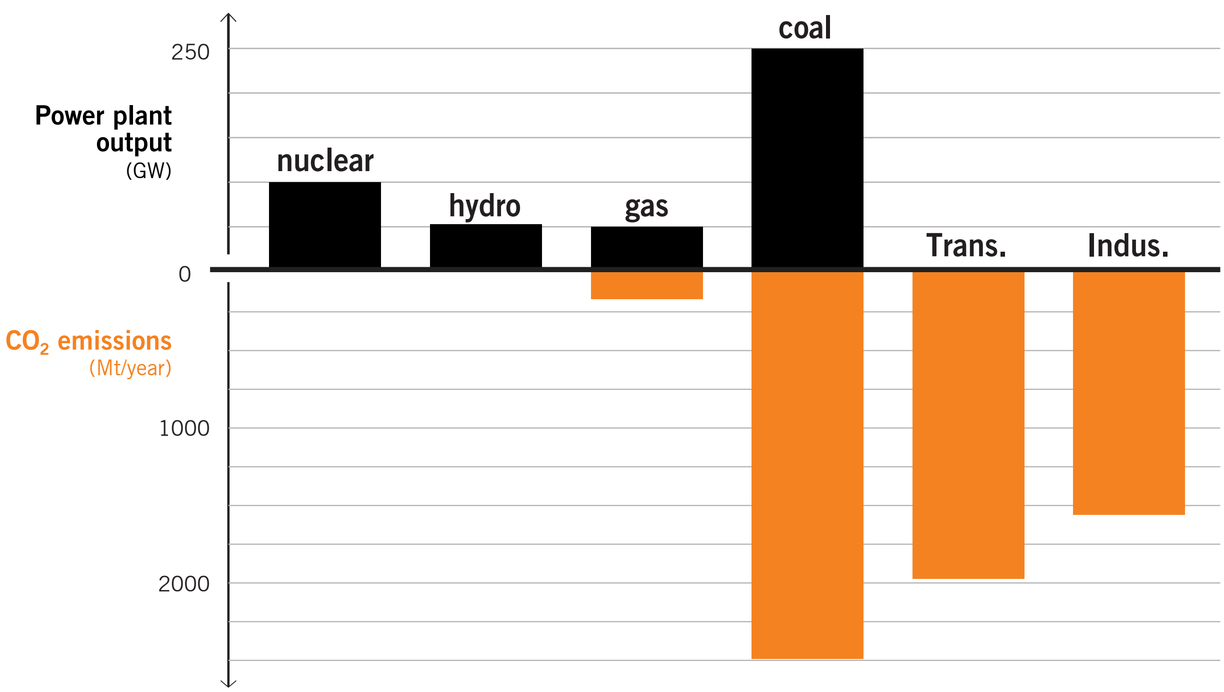


Figure 2: **U.S. power plant output from coal, natural gas, nuclear, and hydro vs. CO_2 emissions from coal and gas power stations, transportation, and industrial, commercial, and residential use**

Coal-fired power stations are the biggest source of CO_2, followed closely by the burning of oil products to power transportation. Together, they emit 70 percent of all CO_2 in the U.S.

The Shape of the Solution

The goal of reducing greenhouse gas emissions and eliminating U.S. dependence on foreign oil has been compared to the effort to put a man on the moon.

In fact, it is much more challenging.

To reduce CO_2 emissions in the U.S. significantly in a timely and practicable manner, it has been proposed *to halve emissions from power plants and transportation by 2040.*

To achieve that goal without carbon sequestration, at least half of the coal-fired power stations must be converted to or replaced with carbon-free power sources. This would require construction starts on new clean power stations with a total capacity of 5 Gigawatts every year for 30 years.

A major effort must be mounted with the aim of halving oil use for transportation by 2040. This should include development and commercialization of truly carbon-neutral cellulosic (not corn-based) bio-fuels as well as light, high-capacity batteries to make hybrid, plug-in hybrid, and electric cars economically attractive.

Both programs require carbon-free, domestic sources of electricity, process heat, and hydrogen to truly reduce U.S. energy dependence and CO_2 emissions.

This will demand strong leadership by the U.S. government and will require full exploitation of all the clean sources of energy which are technically feasible.

There are no easy solutions. It's tempting to think that a dramatic technical advance will solve all our energy problems, but this is wishful thinking. While R&D of all promising technologies should be pursued, the plan for the next several decades must be grounded initially in present technology.

Why the U.S.?

The U.S. has 5 percent of the world's population but consumes 25 percent of the energy used worldwide. It is estimated that the U.S. alone is responsible for more than 20 percent of the greenhouses gases emitted over the last century.

Accordingly, the U.S. has a duty to take the lead in addressing the problem at home. The U.S. government in particular has the responsibility to ensure that its citizens have access to sufficient and affordable energy which is generated in a way that does not endanger our planet. This is a matter of national importance that must not be left only for the markets to decide although they have a major role in its implementation.

Why Now?

By one measure it is already too late—the world is already way beyond the highest known previous concentrations of atmospheric CO_2.

Even if we ignore global warming and keep on burning fossil fuels at the currently accelerating pace, oil and natural gas will become increasingly scarce and expensive. We're then left with coal, the fuel with the highest CO_2 emission rate. "Cleaning" coal by sequestering the resulting CO_2 underground isn't economically feasible on a large scale today. Issues such as large-scale transportation and escape of CO_2 need to be addressed.

What are our choices?

Realistically, any alternative energy source must meet our current energy and economic needs and avoid, as much as possible, our current problems and technological uncertainties. For an alternative power technology to be practical, effective, timely, and truly beneficial, it must fulfill a set of minimal requirements:

- **Pollution** of the environment should be minimal or zero.
- **Waste** must be affordably contained and reliably controlled.
- **Fuel supply** must be adequate for several hundred years.
- **Large-scale** expansion of the technology must be feasible, and have a predictable and acceptable impact on our planet and society.
- **Total cost** of power, "cradle-to-grave" (including mining and waste management), should be known and competitive with fossil fuel technology.
- **Safety** record must be equal or better than that of fossil fuel technology.

These requirements are what it takes for any alternative power technology to be green in a real, meaningful sense. Any so-called "green" technologies that do not fulfill some of these requirements such as large-scale applicability or cost competitiveness, *will likely delay or even block large-scale CO_2 reduction and thereby become detrimental to the environment.*

How green are the major power technologies?

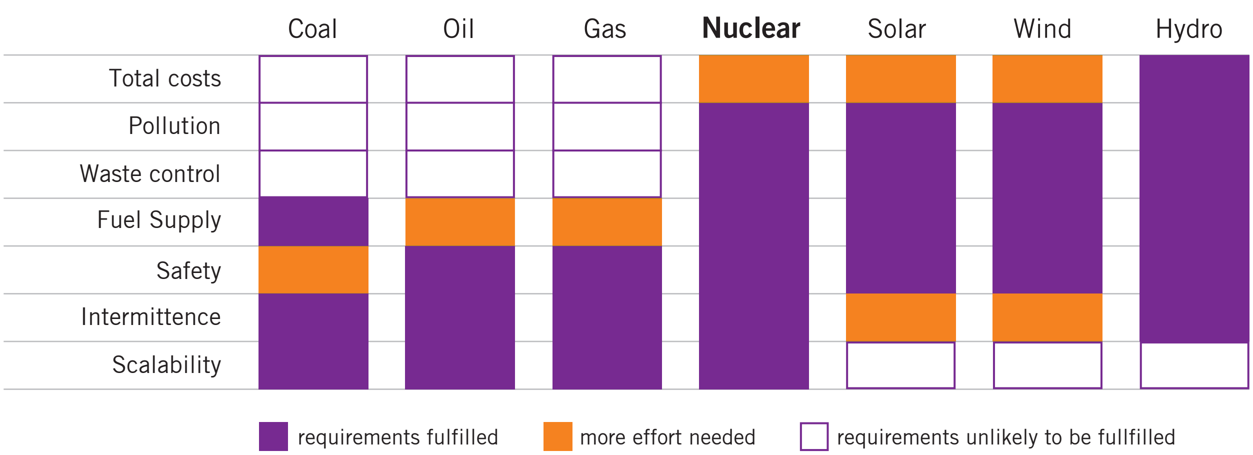


Figure 3: **"Green-ness" of major power technologies**

For "renewables" (wind, solar, hydro, geo-thermal, bio-mass, etc.), large-scale expansion is an unsolved problem. For example, we would need to build 25 "Cape Wind" farms (130 turbines on 24 square miles each) or 30 "Mohave Solar Parks" (10 square miles each) every year for 30 years to replace half of our coal-fired power stations by 2040. In addition, wind and solar power sources are intermittent and would require large-scale construction of new power lines to match power generation with power consumption.

Finally, wind and solar power have yet to establish cost competitiveness. In fact, when the cost of waste management is taken into account, even fossil fuels are unlikely to be cost competitive.

Nuclear power (NP) is the only technology that adequately matches all requirements.

Nuclear power can reasonably undergo large-scale expansion. Five large NP stations would need to be built every year for 30 years to replace half of the coal-fired power stations in the U.S. by 2040 and satisfy modest added needs of transportation and industry.

The U.S. has the capacity to do this. In the 20 years between 1970 and 1990, the U.S. built the equivalent of 100 large nuclear power stations. The yearly investment of 20 to 30 billion dollars or 70 to 100 dollars per person is well within our means. Other countries have also demonstrated that it can be done: France switched to 75 percent nuclear power energy in 25 years without any major problems.

As will be shown in more detail later, waste and used fuel control, contrary to popular belief, are technically feasible (mainly thanks to the extremely low volumes produced.) The safety record for Western-type nuclear power plants is excellent; even the Three-Mile-Island accident produced no fatalities, major injuries, or other health effects. Chernobyl was a Russian-type reactor without containment, subject to an experiment carried out in an unauthorized manner and is in no way indicative of Western reactor safety.

Finally, total projected costs for nuclear power are only moderately higher than the current cost of electricity from coal. The main uncertainty in the cost of new NP plants is a result of today's poor public acceptance driving inflated legal and permitting costs. These can be reversed.

If we are serious about solving the energy supply problem in the U.S. quickly and effectively, nuclear power must become a major ingredient in the mix of power generating technology.

Advantages of nuclear energy

Nuclear fission can be favorably compared to burning coal, oil, and gas. The energy released by nuclear fission of each atom is about 60 million times larger than the energy released per atom by burning carbon and hydrogen.

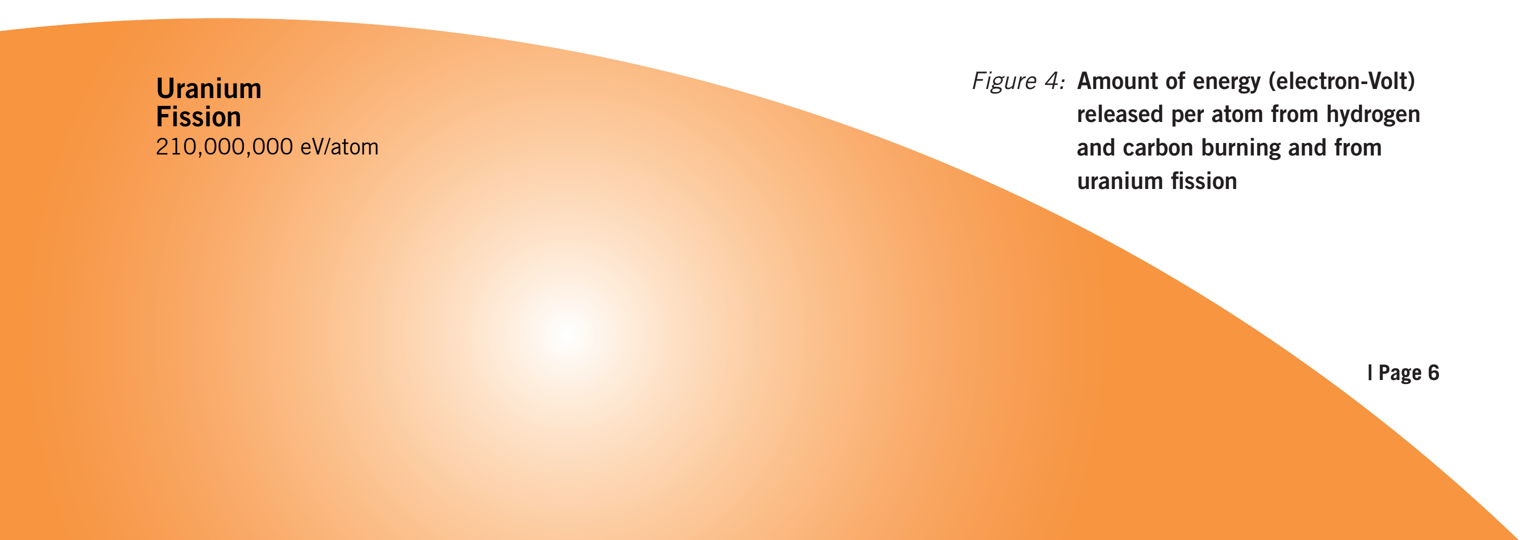


Figure 4: **Amount of energy (electron-Volt) released per atom from hydrogen and carbon burning and from uranium fission**

Therefore, a fossil fuel power plant will burn over a million times more fuel and produce several million times more waste by solid volume than a nuclear plant, to generate the same amount of energy.

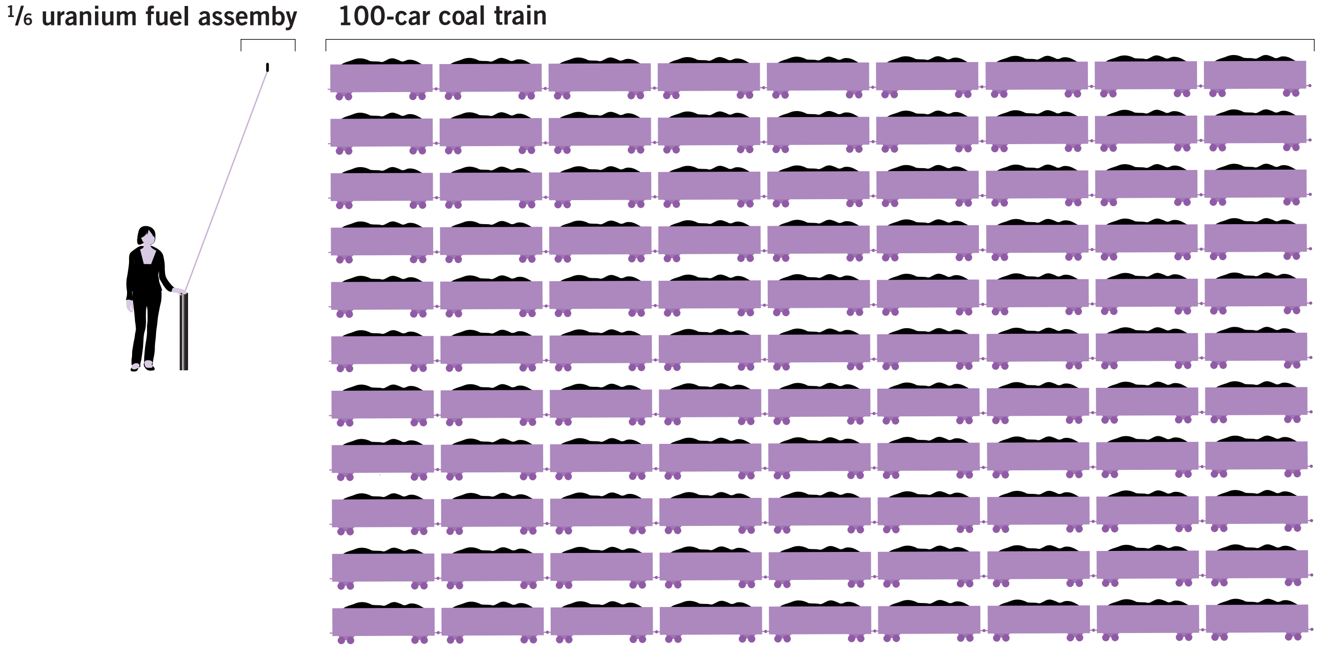


Figure 5: **Amount of fuel needed to power a 1 GW power station (electricity required for about 700,000 US households) for 1 day**

In addition to the physical advantages of nuclear power for electricity generation, it can also provide a carbon-free and efficient source for the vast amounts of heat and hydrogen required to process bio-mass into high-grade hydro-carbon fuels which contain up to 60 percent non-biological energy. Providing this energy from nuclear plants rather than from coal and gas cuts in half the greenhouse gases produced per gallon of bio-fuel.

Counterpoints to Common Objections

We made the mistake of lumping nuclear energy in with nuclear weapons, as if all things nuclear were evil. I think that's as big a mistake as if you lumped nuclear medicine in with nuclear weapons.

—Patrick Moore, former Director of Greenpeace International

The Waste Problem Although the average person is intimidated by the production of radioactive waste, the U.S. government currently manages a much larger volume of irreducible hazardous industrial waste—waste which, just like nuclear waste, must be safely stored.

In 2007, the U.S. produced 46 million tons of hazardous waste—more than 300 pounds per person. Several hundred million tons of non-recyclable waste—an amount the size of one refrigerator per person—are generated annually and wind up in landfills. A sizable portion of the hazardous waste is in the form of chemical elements or very stable compounds which cannot be broken down or eliminated economically by established technologies.

In comparison to the amount and toxicity of this industrial waste, radioactive waste from nuclear power stations in the U.S. is almost invisibly small. The radioactive waste produced by generating a year's worth of electricity for the entire U.S. by NP would be less than one thousandth of today's yearly total of hazardous industrial waste.

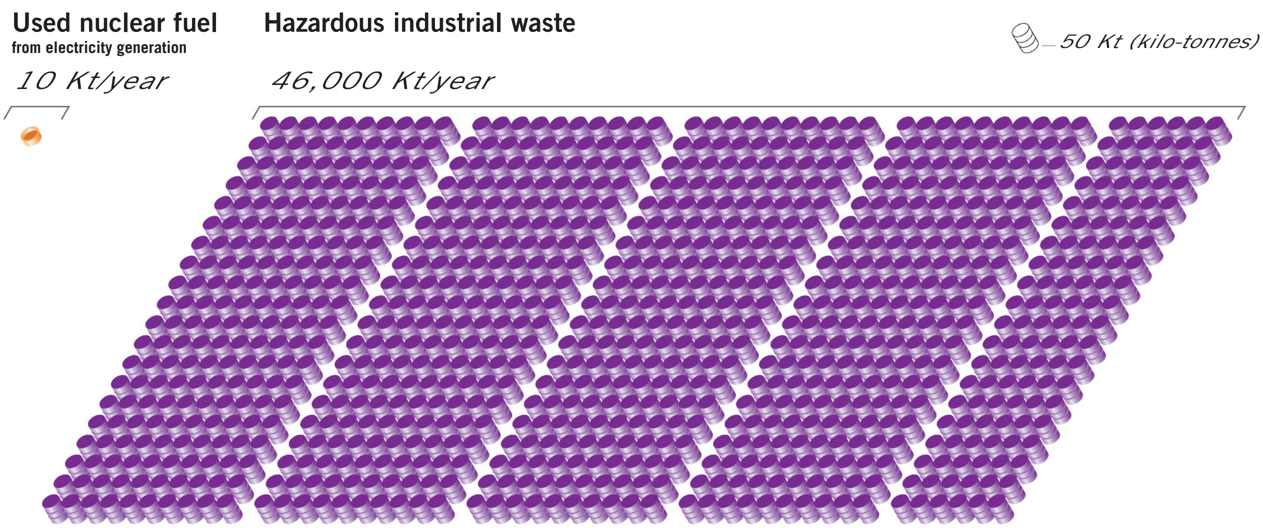


Figure 6: **U.S. hazardous waste production: nuclear waste vs. all other chemical wastes**

Nuclear waste and used fuel Radioactive material from nuclear power stations comes in two kinds: high-activity material, in the form of used-up fuel elements, and low-activity waste. Low-activity waste, similar to the kind of radioactive waste generated by hospitals and manufacturing, decays in a few hundred years to safe levels and can be reliably stored with conventional technology. However, high-activity material contains radioactive elements which decay over many thousands of years and needs to be treated and stored appropriately. This material remains manageable, because of the low volume produced.

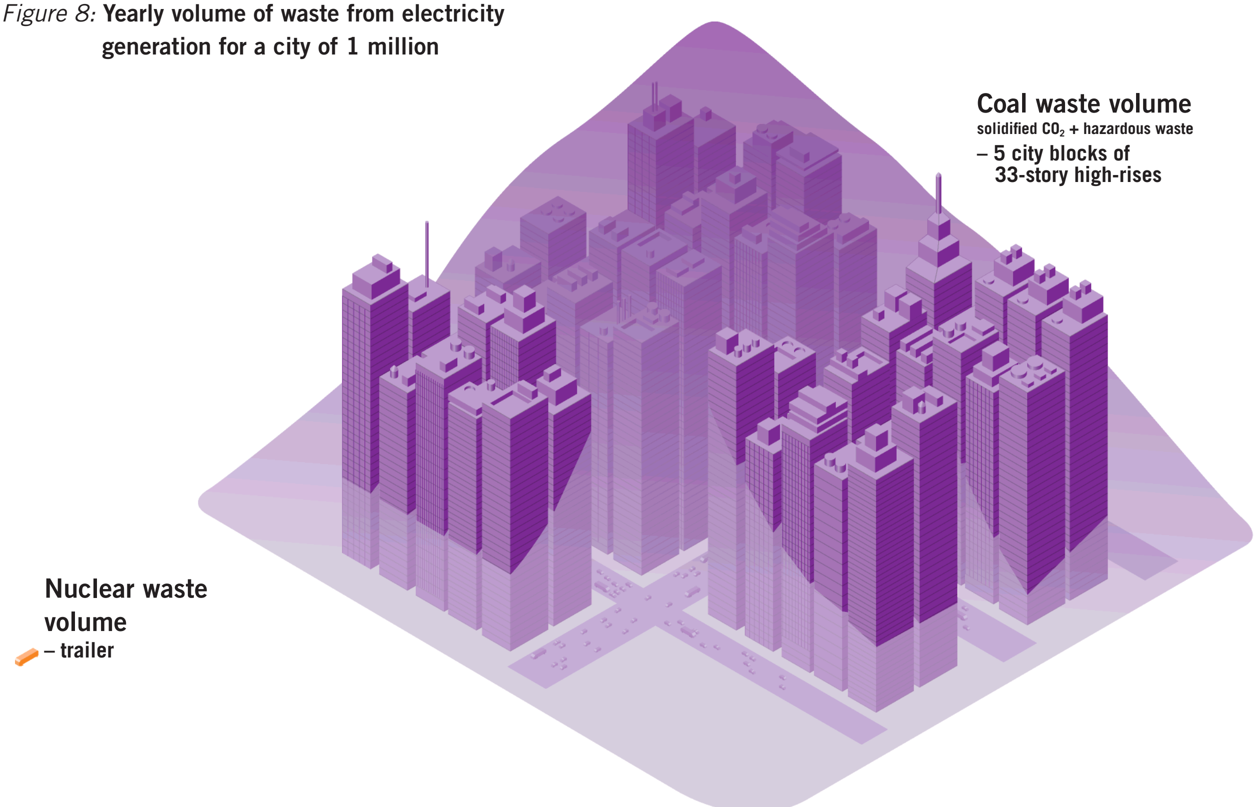
The high-activity material produced by one person's yearly use of electricity generated by NP would be the size of a D-battery. The total high-activity material created yearly by generating power for a city of one million inhabitants and their businesses and industry would easily fit into a trailer. That space includes the shielding necessary to reduce the radiation from this material to a level much lower than we experience naturally in everyday life. Such a small volume can be stored and controlled indefinitely for a modest cost. Even if permanent "bury-and-forget" disposal should prove not feasible, nuclear material would be a tiny addition to the very much larger hazardous industrial waste we have to store and monitor permanently.

In contrast, one person's yearly coal-powered electricity use produces a volume of CO_2 waste which, if converted to solid form, would fill ten large refrigerators.

Figure 7: **Yearly waste from electricity generation per person: nuclear vs. coal**

Yearly waste, mainly CO_2, from electricity production for a city of one million would be the size of a 400 foot high mountain covering 30 acres—once we succeed in converting the fossil fuel waste into solid form. In the gaseous form, the volume is one thousand times larger still.

Figure 8: **Yearly volume of waste from electricity generation for a city of 1 million**



This waste is mainly CO_2 but also contains millions of tons of sulfur dioxide and nitrogen oxide as well as tons of other toxic materials like mercury, arsenic, lead, and radioactive thorium and uranium. Although less toxic pound for pound than nuclear material, its sheer volume makes it practically unmanageable and uncontrollable. As a result, CO_2 is simply discharged into the environment with consequences which we have only now begun to appreciate. Burying these wastes deep underground (carbon sequestration)—economically and on the scale required—is still an unsolved problem.

Safety In the western world (OECD), over 300 nuclear power stations produce on average 300 Gigawatt (GW) of electricity—about 25 percent of the total electric power. They do this with fewer industrial fatalities each year than result from U.S. coal mining alone.

The infamous and disastrous accident at the Chernobyl reactor in the Ukraine in 1986 was the result of an inherently unstable reactor design, quite different from Western reactors. The Chernobyl reactor was not housed in a protective containment building as all Western reactors are. As a consequence, when safety experiments carried out in an unauthorized manner on the reactor resulted in a run-away power build-up, the reactor exploded killing some forty workers and spreading radioactive material over large areas. Even so, the death toll from Chernobyl is less than one year's toll from air pollution. All commercial

Western reactors are designed in a fundamentally different way to eliminate the possibility of a catastrophic power excursion.

The Three-Mile Island reactor suffered a series of malfunctions in 1979 which resulted in a partial melt-down of the reactor core. But in contrast to Chernobyl, there was no run-away reaction in this Western-style reactor.

The radioactive emissions from the molten reactor core were held back almost entirely by the safety containment of the reactor. People living in the neighborhood of Three-Mile Island received a radiation dose of less than one percent of their natural yearly exposure. There were no fatalities or health effects resulting from the accident. It demonstrated that Western-type reactors are safe even in case of severe malfunctions and operator errors.

Comparative Cost of Nuclear Power Plants The cost of obtaining electricity from future NP stations has been investigated in a number of studies, including an interdisciplinary MIT study updated in 2009. Assuming strictly commercial, unsubsidized plant construction and operation, including fuel, waste management, and decommissioning, the estimated electricity cost is about 6.5 cents per kilo-watt-hour (kWh). Other studies like the Organisation for Economic Co-operation and Development (OECD) comparative study of 2005 projected the lower cost of 5.7 cents per kWh for a ten percent discount rate on investment. This compares with about 5 to 5.5 cents per kWh from the cheapest current source—powdered coal without waste management. For the customer, nuclear power is only five to ten percent more expensive than the cheapest coal power.

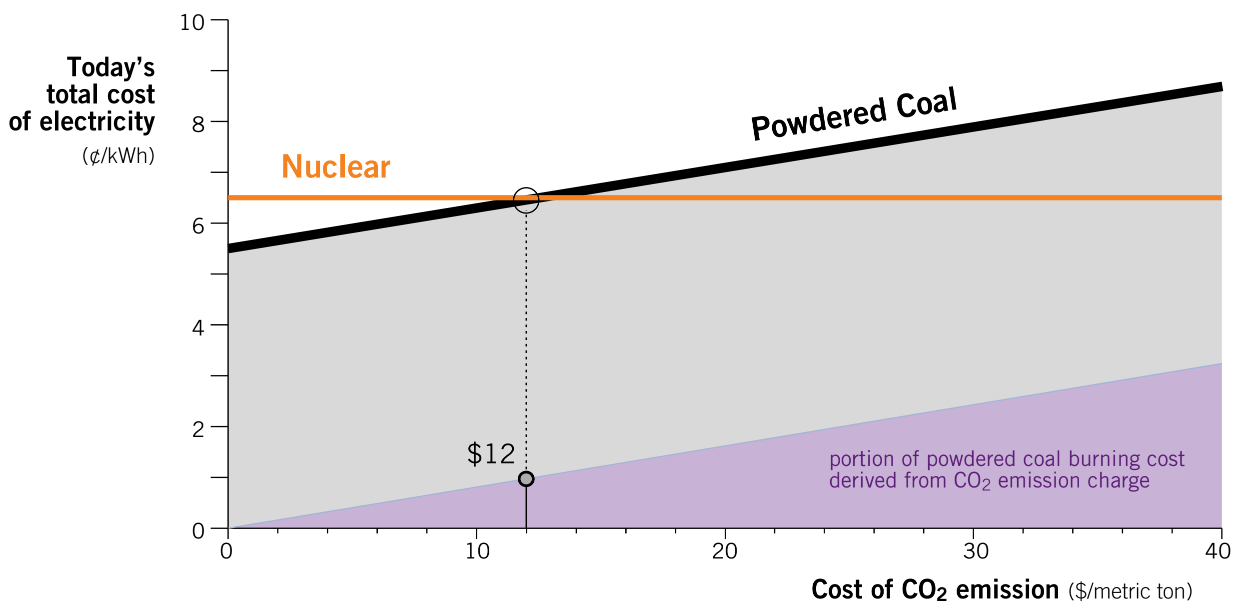


Figure 9: **Total cost of electricity from nuclear and coal plants, including the cost of waste management (MIT study)**

The cost of NP is dominated by the cost of financing the power plant (about 75 percent of the total cost). Plant cost has been inflated by extending construction time, or by requiring expensive retrofitting during construction through litigation and political action. One notable example of such practices is the two-fold cost overrun caused on the construction of the Shoreham Plant on Long Island, NY, after which it was never even allowed to operate.

Obstructionism of this kind could make any energy source economically unacceptable. The government must provide the legal and financing framework to allow any future energy source to operate on equal footing with current technologies.

Fuel supply Western (OECD) nuclear power production consumes about 53 thousand tons of uranium per year. Total world uranium consumption is about 60 thousand tons per year. Increasing NP to 75 percent of the OECD's electricity needs would require 160 thousand tons of uranium per year.

In 2007, the U.S. Nuclear Energy Agency (NEA) and the International Atomic Energy Agency (IAEA) reported proven and estimated uranium deposits of 5.5 and 10.5 million tons respectively that can be mined below today's market price of $130/kg. At present electricity use, these deposits could supply the West's uranium needs for 100 years even if all fossil-fueled power stations were converted to nuclear.

Uranium exploration is still in a very early stage, similar to what oil exploration was one hundred years ago. Substantial new deposits and new extraction technologies will likely be identified in the future. Furthermore, fuel reprocessing and breeder reactors can be expected to stretch this fuel supply to many centuries.

Nuclear fuel supply is also highly reliable for two reasons: Uranium is generally available from politically stable regions like Canada and Australia and it can easily be stockpiled for many years, which eliminates fuel price speculation. A stockpile of 700,000 tons of uranium could power the entire U.S. for ten years without using fossil fuels. This amount could be stored in a warehouse the size of a football field.

Proliferation, theft of nuclear materials, terrorist attacks Proliferation of nuclear technology to foreign states intent on nuclear weapons development is not an issue for nuclear power stations operated in the U.S.

Theft of radioactive material from nuclear power stations is extremely difficult. The only weapons-grade material is plutonium accumulated in fuel rods during months of plant operation. The rods have to be extracted by crane, emit deadly radiation, and would have to be transported to a specialized facility to extract the plutonium. Thus, it would be extremely difficult and probably lethal to steal radioactive material from a nuclear power plant.

A power reactor, by virtue of its fuel composition, cannot explode as a nuclear bomb. To access the reactor, terrorists would need to breach multiple security barriers and circumvent safety measures requiring detailed technical inside knowledge of the plant. Even then, the worst result that they could cause would likely be a reactor melt-down that would cause serious plant damage but have little if any impact on the surroundings of the plant. The same holds for external attacks by mortars or rockets or by crashing an airplane into the reactor building.

Nuclear power plants of Western design are very hard targets to attack. There are numerous softer targets available like refineries, liquid gas terminals, or chemical plants. Nuclear plants add little to the already existing risk of terrorist attacks.

How do we move forward?

To reach a goal of 50 percent nuclear electricity generation in the U.S. by 2040 requires us to *rethink* some of the assumptions that have governed nuclear power development in the past:

Nuclear power should *replace* coal-fueled power stations as they age and are phased out as well as adding new generating capacity at least until carbon sequestration proves economical on a large scale. Cap-and-trade for CO_2 emissions, a carbon tax, or required CO_2 sequestration could all help make conversions of coal-fired plants to NP commercially attractive. CO_2 emissions will remain unmanageable as long as coal-fired plants are not phased out or CO_2 is sequestered.

Used fuel elements (currently labeled "high-level radioactive waste") do not have to be immediately buried in geological repositories ("Yucca Mountain") but can be stored indefinitely in secure monitored regional facilities. Such *managed storage* is affordable because of the small fuel volume. It also leaves open the option of recycling the fuel to extract vast amounts of additional energy in future generations of reactors. Eventual permanent but monitored and retrievable storage in geological repositories does not require proven integrity over hundreds of millennia which is needed for unmanaged burial sites.

The government has to provide the **legal, political, and financing framework** to make nuclear electricity generation a predictable, attractive investment. This would allow modest financing costs—something more in line with those of a long-term mortgage rather than a high-risk capital venture. The government could also consider streamlined permitting and licensing rules, promoting standard reactor designs including small, mass-produced reactors, which are certified for construction requiring only additional site permits, as well as low-cost financing for a number of industry-built "demonstration" plants to establish commercial feasibility of nuclear electricity generation.

Finally, the massive expansion of nuclear power must be initially based on **existing reactor technology** to meet the necessary timetable for CO_2 reduction. Enhanced R&D in future reactor and fuel cycle technologies are expected to extend nuclear power sustainability into the next centuries.

To halve oil consumption for transportation in the U.S. by 2040 requires a shift away from gas and diesel engines to electric motors as well as substantial replacement of oil with carbon-neutral domestic bio-fuels:

Battery and hydrogen storage technology for cars and trucks has to be developed with high priority and government support.

Energy-rich, carbon-free cellulosic bio-fuel production from switch grass and agricultural waste rather than from corn and processed with heat and hydrogen from NP plants has to be developed for large-scale applications.

Carbon-free **hydrogen generation** with high-temperature nuclear reactors needs to be studied and developed industrially.

Conclusion

The proposed expansion of NP to replace coal fired power stations and to provide process heat, hydrogen, and electricity for bio-fuels and electric cars would halve CO_2 emissions from electricity generation and transportation. The result is illustrated in the following figure 10 in which the areas of the columns indicate the amounts of CO_2 emitted yearly.

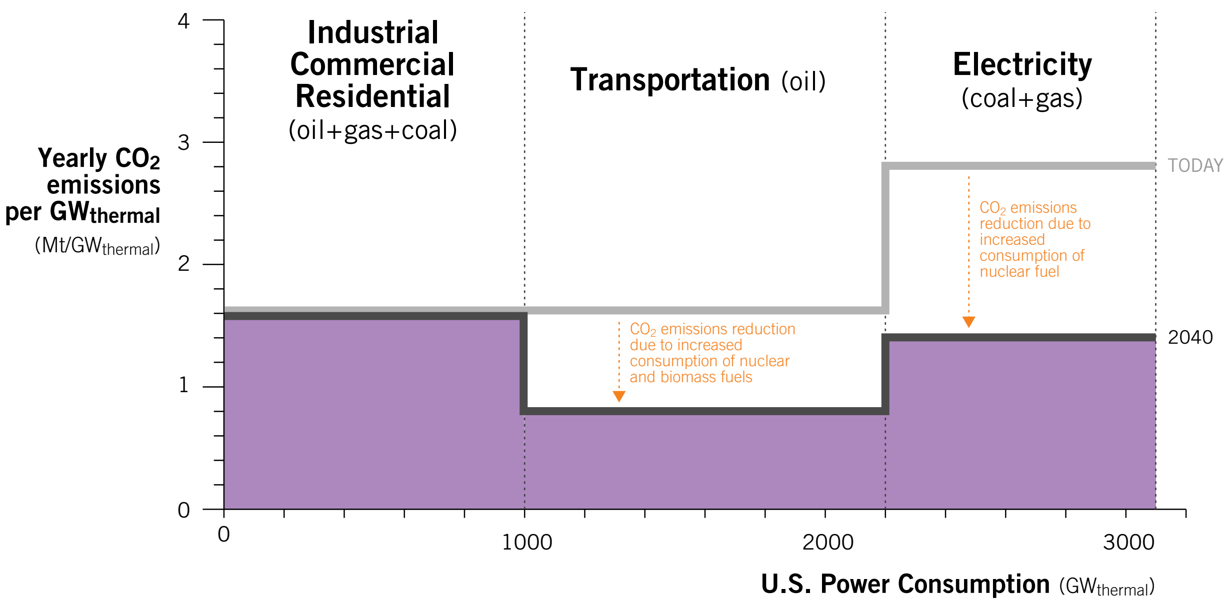


Figure 10: **Reduction of CO_2 emissions by expanding nuclear power and cellulosic bio-fuel**

Nuclear power as an electricity generator and an enabler of low-carbon bio-fuel production has the potential to reduce the total U.S. emissions of CO_2 by one third.

Paired with serious energy saving efforts, today's greenhouse emissions and oil consumption by the U.S. could be halved without lowering our quality of life.

Synopsis

- CO_2 emissions from fossil-fuel burning may be endangering the planet.
- The United States' dependence on foreign oil threatens the country's energy security.
- Both problems require the immediate start of large-scale conversion from fossil fuel to non-polluting, oil-free energy sources.
- The requirements for sustainable energy sources are: minimal pollution, controlled waste stream, ample fuel supply, mature technology proven in large-scale deployment, affordable cost, and proven safety record.
- The only technology fulfilling **all** requirements today is nuclear power (NP). In contrast to the cheapest power source, coal, NP is inherently non-polluting, its waste volume is over a million times smaller than coal, its safety record excellent, and its cost only moderately higher. It can readily replace coal-fired power stations and provide process heat and hydrogen to produce bio-fuels and heat for industrial, commercial, and residential use.
- Legal, political, and financing measures are required to level the playing field for nuclear-fuelled relative to coal-fuelled power plant construction and operation, including comparable standards for management of nuclear and fossil fuel wastes (by carbon sequestration or carbon tax).
- Conversion of electricity generation from coal to 50 percent nuclear together with replacement of 50 percent of oil for transportation by electricity and cellulosic bio-fuel processed by nuclear power (NP) can reduce U.S. CO_2 emissions by one third. To achieve this by 2040 requires yearly building starts on new NP stations generating 5 GW, a construction rate already achieved in the U.S. in the 1970s and 1980s. To the extent that the carbon sequestration becomes economical in the future, the remaining coal-fired plants can become low-carbon emitters, further reducing CO_2 emissions.