# Vision 21: Ultra-Clean Energy Plants for the 21st Century

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## INTRODUCTION

Vision 21 is the U.S. Department of Energy's new initiative for developing the technology needed for ultra-clean 21st century energy plants. The goal of Vision 21 is to effectively remove, at competitive costs, environmental concerns associated with the use of fossil fuels for producing electricity and transportation fuels.

The Vision 21 initiative is timely because of the confluence of energy, environmental, and market drivers. These drivers include:

- growing energy demand, particularly for electricity, both in the U.S. and worldwide
- a recognition that fossil energy needs to be part of the future energy mix
- the need to "solve" environmental concerns associated with fossil fuel use
- restructuring of the energy industry with new players open to multiple feedstocks and products, and an under-investment in research and technology development
- recognition of the value of "future options," such as the hydrogen economy

Achieving the Vision 21 goal will require an intensive, long-range 15-20 year, research and development effort. Industry involvement, beginning at the planning stages, is necessary in order to build the commitment needed and to help ensure market relevance of new technologies. Cost-sharing is required. Instead of emphasizing evolutionary improvements in existing technologies, Vision 21 stresses innovation and revolutionary technologies. These conditions are necessary if Vision 21 is to be successful at developing the technology basis for 21st century energy plants with unprecedented efficiency and environmental performance.

Vision 21 is fundamentally different from the traditional DOE Fossil Energy R&D program to develop improved power system technology. The previous approach addressed different areas of power technology separately. However, any *single* approach, e.g., gasification combined cycle, advanced turbine systems, fuel cells, advanced pulverized coal combustion, indirectly fired cycles, and pressurized fluidized bed combustion, cannot achieve the efficiency, environmental performance, and economic performance that will be needed in Vision 21 plants. Where Vision 21 differs from the current R&D portfolio is that Vision 21 aims to *integrate* multiple advanced technologies in order to create systems that achieve breakthrough improvements in performance and cost. Other differences are Vision 21's emphasis on market flexibility, multiple feedstocks and products, and industrial ecology.

## PERFORMANCE TARGETS FOR VISION 21 ENERGY PLANTS

Table 1 shows the performance targets, including costs and timing, for Vision 21 energy plants. Targets are clearly very aggressive, especially since designs for commercial plants are to be developed in only 15 years. An added benefit is that spinoff technologies, some available before 2005, are likely to result from Vision 21 R&D. These spinoffs, which are expected to have applications beyond the power and energy industries, could include low-cost gas separation technology (e.g., for $H_2$ from syngas and $O_2$ from air), better gas purification/cleaning processes, better catalysts for producing fuels and chemicals from low-valued raw materials, more efficient and lower cost environmental control technology, high-temperature heat exchangers, and improved materials for service under high-temperature conditions.

## VISION 21 TECHNOLOGIES

Vision 21 focuses on developing the key, critical technologies that will be needed to design and build Vision 21 energy plants. Specific types of plants or plant configurations are not emphasized because it is unknown what kinds of plants, feedstocks, and products the market will favor 15-20 years into the future. DOE has no intention of imposing on the market any preselected approaches, technologies, or kinds of plants. At the first Vision 21 industry workshop, held in Pittsburgh in December 1998, DOE and industry worked together to identify the key technologies that are most likely to be needed in future Vision 21 plants, regardless of the specific plant configuration. These technologies include:

- fuel-flexible, thermally efficient gasification to allow the use of low-cost feedstocks, e.g., municipal waste, petcoke, and biomass, with coal
- gas separation, e.g., membranes that can be used to separate oxygen from air, hydrogen from syngas, and $CO_2$ from combustion products
- high-temperature heat exchangers, e.g., alloy-tube exchangers capable of heating steam or air for use in advanced, high-efficiency cycles
- gas stream purification systems capable of operating at high temperatures for removing sulfur compounds and other constituents that may corrode or erode downstream components, e.g. turbines, or poison downstream catalysts
- high-performance combustion systems, both suspension-fired and fluidized bed, including ultra-low-NOx combustion and systems that burn fuels in $O_2/CO_2$ mixtures and produce exhaust streams containing only $CO_2$ and water
- fuel-flexible combustion turbines and engine systems, especially turbines and engines capable of operating on coal-derived gases or hydrogen; fuel cell/turbine-engine hybrids capable of 70-80% efficiency; advanced combustion turbines, including ceramic turbines and engines; advanced steam turbines

- fuel cells, e.g., high-efficiency, low-cost fuel cells; cascaded fuel cell systems capable of operating at multiple temperatures and pressures; fuel cells bottomed by fuel cells; fuel cell/turbine hybrids; new, low-cost, fuel cell concepts capable of approaching $100/kilowatt stack costs and, when incorporated into a system, 70-80% system efficiency
- advanced fuels and chemicals development; systems and catalysts for fuels and chemicals production; hydrogen production and storage
- advanced materials for high-temperature applications in aggressive environments, e.g., boiler tubes for high-temperature steam bottoming cycles, and very high-temperature (>2000$^o$F) heat exchangers for use in indirectly fired cycles and other applications, as well as functional materials needed for gas cleanup or separation
- advanced controls and sensors for highly integrated Vision 21 plants; new algorithms that utilize state-of-the-art hardware to assure reliable performance, optimum plant efficiency, and low emissions
- environmental control technology for low-NOx emissions, control of fine particulate matter, and management of byproducts from Vision 21 plants; improved concepts for $CO_2$ capture and separation
- computational modeling and virtual simulation.

Vision 21 has unique system integration issues. Systems integration comprises systems engineering, dynamic response and control, and industrial ecology. Systems engineering concerns the configuration of Vision 21 plants, the design of components and subsystems, and subsystem interconnections. Good systems engineering ensures that components and subsystems are compatible with one another, that the design of the plant is as simple as practicable, and that plant capital and operating costs are as low as possible. High thermal efficiency requires “tight” integration of subsystems in order to achieve maximum heat recovery, maximum utilization of feedstocks, and minimum production of disposables. However, tight integration leads to complex interdependencies among the various subsystems, potentially leading to serious startup, control, and reliability issues. New control strategies and improved control software and hardware will need to be developed. Vision 21 also offers opportunities for industrial ecology, i.e., utilizing output streams that would otherwise be considered waste as input streams for additional processing or recycle. Ideally, the application of industrial ecology principles would eliminate all waste products.

Vision 21 will need substantially improved design and simulation tools, including development of a virtual simulation capability. These tools will be used to aid in designing individual components and subsystems, to evaluate and compare the performance of different configurations of Vision 21 systems, and to simulate the performance of plant sections and complete Vision 21 plants. Availability of advanced simulation software will reduce the cost of developing Vision 21 systems. Development of this capability will be a key part of the Vision 21 program.

## THE ROLE OF GASIFICATION IN VISION 21

The drivers favoring gasification in Vision 21 plants are product slate flexibility, efficiency, and emissions, particularly separation and sequestration of $CO_2$. The gasifier fuel gas product, once cleaned, can be used to make multiple products including electricity, steam, clean transportation fuels, chemicals, hydrogen, and substitute natural gas. Cleaning can remove nearly all of the sulfur and nitrogen compounds and particulate matter from the fuel gas, thereby achieving near-zero emissions of sulfur and nitrogen oxides and particulate in applications where the gas is burned to produce power. In such applications, such as combustion in a gas turbine, use of advanced combustion technology could result in near-zero emissions of thermal NOx. Gasification processes are readily adaptable to $CO_2$ separation and sequestration. The concentration of $CO_2$ in the gasifier fuel gas is much higher than in a typical combustion flue gas. The fuel gas is also pressurized, which reduces the gas volume to be processed and the amount of energy required to convert the gaseous $CO_2$ to a liquid. Gasification can be readily integrated with fuel cells to produce electricity at unprecedented high efficiencies.

Figure 1 shows an artist's rendition of a gasification-based Vision 21 plant. The gasifier produces a fuel gas which is cleaned and used to produce power with gas turbines and fuel cells as well as clean transportation fuels and chemicals. The plant features modular design and makes a market-driven product slate. Coal and "opportunity" feedstocks are gasified using oxygen produced with a low-cost air separation membrane. The fuel gas is cleaned and a second membrane is used to separate hydrogen. Carbon monoxide in the fuel gas may be shifted to $CO_2$ and the $CO_2$ sequestered if necessary. Electricity is generated with a fuel cell using the hydrogen and a gas turbine using the energy in the fuel cell exhaust. Heat remaining in the gas turbine exhaust is used to generate steam for process heating. A portion of the fuel gas is diverted for the production of clean liquid fuels and high-value chemicals.

It needs to be emphasized that all Vision 21 plants will not produce a slate of products nor utilize multiple feedstocks. Indeed, is is likely that electricity will be the major or only product most of the time. Other products, such as clean transportation fuels, would be produced where it makes economic sense, i.e., where it lowers the cost of producing electricity. The important point is that gasification provides the *option* of coproduction. Just as DOE has no intention of imposing preselected technology on the market; similarly, DOE believes that choices concerning products and feedstocks should be based on market and economic forces.

Figure 2 shows a gasification/gas turbine/fuel cell cycle that was created to determine how a coal-based system might be configured to achieve the Vision 21 efficiency target of 60 percent for electricity production. This system was designed for study purposes and we are not implying that it is a likely configuration for a future commercial Vision 21 plant. However, the heat and mass balance indicates that it is thermodynamically feasible to achieve 60% efficiency (HHV) using coal as the fuel. The gas turbine, fuel cell, and gasifier technology selected for the cycle represent the state-of-the-art in DOE's current development programs. Many of the subsystems and components in Figure 2 have not been tested at the scales or operating conditions of a large commercial plant. The challenges are to integrate the subsystems at the correct sizes and conditions, simplify the cycle, develop a control strategy and the means to implement it, and reduce cost.

The design shown produces 560 MW (gross) or 520 MW (net) power. The fuel is Illinois No. 6 coal containing 2.5% sulfur. The coal is gasified in an entrained bed gasifier operating at 15 atm. pressure. A cold gas conversion efficiency of 84% is assumed. The fuel gas is cleaned, cooled, and desulfurized before entering a solid oxide fuel cell (SOFC) operating at 15 atm. and 1830$^{o}$F. A portion of the gasifier fuel gas is reduced in pressure through an expander/turbine before entering a second, low pressure, SOFC operating at 3 atm. Ninety percent of the fuel constituents are converted within the cell chambers to produce electricity. The remaining fuel is combusted with the oxidant exhaust streams from the SOFC cathodes to boost the heat energy available for use in the two cascaded turboexpanders. Heat from the turbine exhausts and from the fuel gas cooler is used to generate steam for a reheat steam cycle operating at 1450 psi and 1000$^{o}$F. Of the 560 MW gross power, 33% is provided by the high-pressure SOFC, 21% by the low-pressure SOFC, 25% from the turboexpanders, and 21% from the steam turbine.

## VISION 21 PROJECT PORTFOLIO

The Vision 21 project portfolio comprises ongoing activities in various NETL product areas, e.g., gasification, combustion, turbines, fuel cells, environmental technology, clean fuels, and advanced research, that relate to achieving Vision 21 objectives. In addition, DOE issued a Vision 21 solicitation in September 1999 to competitively seek additional cost-shared projects to develop technologies and analytical capabilities needed for Vision 21. Thirteen projects, out of over nearly 70 proposals received, have been selected as of August 2000. Their combined value is approximately $32 million, with about $8 million being provided by the participants and $24 million by DOE. Although the ongoing activities and new projects address a diverse set of technologies, they collectively share a singular theme and constitute the Vision 21 program. The common theme is the focus on developing the technology and know-how needed to design the subsystems and components that make up Vision 21 plants. Brief synopses of the recently selected Vision 21 projects are provided below.

- A team led by the National Fuel Cell Research Center, Irvine, CA, will define the engineering issues associated with integrating key components and subsystems into Vision 21 plants. Issues that will be addressed include startup, shutdown, and transient operation of systems that include gas turbines and fuel cells. This work will provide the insight needed to use combinations of advanced technologies in practical systems that can achieve Vision 21 performance objectives.

- Princeton University, Princeton, NJ, will develop computer software to simulate gas-particle flow over a range of conditions, including those encountered in fluidized bed and entrained flow gasifiers, fluidized bed combustors, and pneumatic transport. A unique benefit of this new software will be that it is to use a coarse computational grid that does not require excessive amounts of computer time, and yet will still provide detailed simulations of gas-particle flow.

- Reaction Engineering International, Salt Lake City, UT, will lead a team that will develop a computational virtual "workbench" for simulating the performance of Vision 21 energy plants.

The workbench will allow models that vary greatly in complexity, for example simple mass and energy balances to complex chemical kinetics and fluid dynamics codes, to "communicate" with one another in a seamless manner.  This capability will allow engineers to assess the impacts of changes in operating conditions on system performance and to evaluate a wide variety of plant configurations while substantially reducing expensive testing.

- Fluent, Lebanon, NH, will begin building a virtual simulation system that would give future plant designers a way to model a fully functional Vision 21 plant on a computer. Submodels for Vision 21 plant subsystems and components, dynamic response and control, and visualization will be linked so that Vision 21 systems can be more readily designed and simulated.  Designers would be able to explore a wide range of parameters and to optimize plant subsystems and components in the context of the whole process rather than in isolation. Other benefits of virtual simulation may include increasing the confidence of potential customers in Vision 21 technology.

- CFD Research, Huntsville, AL, along with team members and an industrial consortium comprising turbine and combustion equipment manufacturers, will apply an advanced computational tool called "large eddy simulation" to design low-emission combustion systems for gas turbines.  Using a computer to simulate the effect on emissions caused by changes in fuel composition or combustor design can reduce the costs of developing new, more efficient, and cleaner combustor designs and lead to innovative concepts for reducing emissions.

- Huntington Alloys, Huntington, WV, and its partners will develop stronger, heat- and corrosion-resistant Oxide Dispersion Strengthened (ODS) alloys for Vision 21 heat exchangers and other applications not possible with existing metallic materials.  ODS alloys retain their strength at very high temperatures but their application is limited by poor weldability and relatively poor circumferential creep strength.  This latter property will be improved by modifying the grain structure so that ODS tubing can be used at high-temperature (c. $2000^{o}$F), high-pressure conditions that will often be encountered in Vision 21 plants.  Improved joining methods will also be developed and high-temperature corrosion limits will be established.

- Clean Energy Systems, Sacramento, CA, will develop a "rocket engine" steam generator to power an advanced turbine, generating electricity and emitting only water and a stream of $CO_2$ ready for sequestration.  Efficiencies exceeding 60% can be achieved with turbines operating at 3000 lb/in$^2$ and $2600^{o}$F.  The size of the steam generator is dramatically smaller than boilers used today; a unit of several hundred megawatts capacity would be about the size of an office desk, opening up possibilities for transportability and greatly reduced cost.

- Fuel Cell Energy, Danbury, CT, will begin developing a "hybrid" power system that would combine a fuel cell and gas turbine to generate electricity at efficiencies unprecedented even for gas-based systems, 65% (near-term) to 80% (by 2015).  An existing 250 kW fuel cell will be combined with a commercially available microturbine and a conceptual design of a 40 MW

Vision 21 plant will be prepared. The proposed system uses a novel approach in which the heat energy in the fuel cell exhaust is transferred indirectly to the turbine air with heat exchangers. A benefit of this approach is that the fuel cell can operate at ambient pressure, saving the costs of piping and pressure vessels, and allowing the turbine to operate at its optimum pressure ratio.

- Foster Wheeler Development Corporation, Livingston, NJ, will lead a team developing a pressurized circulating fluidized bed partial gasification module that offers the advantages of gasification while providing substantial process flexibility because it produces both solid and gaseous fuels that can be utilized in advanced steam and gas turbine cycles. The module also operates at much lower temperatures than existing gasifiers, potentially improving reliability and reducing operating costs.

- GE Energy and Environmental Research Corporation, Irvine, CA, will develop an innovative, fuel-flexible gasification-combustion concept to convert coal and opportunity feedstocks to hydrogen and a separate stream of sequestration-ready $CO_2$. The hydrogen could be used in fuel cells and combustion turbines to generate electricity with zero pollutant emissions. The three-year program includes lab-, bench-, and pilot-scale activities.

- Eltron Research, Boulder, CO, and ITN Energy Systems, Wheat Ridge, CO, will develop alternative approaches for using non-porous membranes to separate hydrogen from gas streams such as those from coal gasification. In this approach, the hydrogen-containing gas mixture is passed across the membrane surface where hydrogen is catalytically oxidized. The protons and electrons generated are incorporated into the membrane material lattice and conducted to the reduction surface on the other side of the membrane where the reverse reduction reaction occurs to produce pure hydrogen. The technical challenge is to create materials that have both satisfactory proton and electron conductivity and chemical stability at the conditions of use, and to develop thin ceramic structures that achieve hydrogen separation rates comparable to those used in industrial processes.

- Siemens-Westinghouse Power Corporation, Pittsburgh, PA, will team with Praxair, Tonawanda, NY, to develop a zero-emission power plant that integrates a solid oxide fuel cell (SOFC) with an oxygen ion-transport membrane (OTM). The approach will be to modify the design of a tubular SOFC by including a stack of OTMs. Oxygen transported through the membrane would be used to oxidize the SOFC's depleted fuel, converting it into $CO_2$ and steam. The $CO_2$ can be easily separated for eventual sequestration by condensing the steam. OTM technology provides a much more efficient method of supplying oxygen than conventional cryogenic air separation. In addition, the comparable operating temperatures of SOFCs and OTMs allow for an energy-efficient and cost-effective integration.

## NATIONAL RESEARCH COUNCIL ASSESSMENT

The National Research Council (NRC) recently completed a one-year study, commissioned by the DOE's Office of Fossil Energy, to review and comment on the early planning for the Vision 21 program. The review committee, which was headed by an electric utility executive, involved a broad cross-section of experts from the energy industry and academia. The committee's report, which is available from the NRC, strongly endorsed Vision 21[1]. With respect to Vision 21's goals, the committee stated:

> "The goals for the Vision 21 program are very ambitious. If these goals can be achieved, Vision 21 technologies would offer the United States, and the world, a new method of coal-based power generation that would have significant advantages over current methods."

**WHAT'S IMPORTANT?**

In summary, the points that distinguish Vision 21 from traditional approaches to improving fossil energy technology are:

- leapfrog performance improvement
- near-zero environmental impact
- zero $CO_2$ emission option
- feedstock and product flexibility
- industrial ecology (no waste generation)
- technology development focus
- systems integration

**WHAT'S NEXT?**

The Vision 21 R&D Roadmap is being revised as a result of industry recommendations developed at a Vision 21 Industry Roadmapping Workshop held at the University of Maryland in August 2000. The revised Roadmap will be a detailed 15-year plan that defines specific Vision 21 objectives, technical barriers, and activities for overcoming the barriers, for each of the key Vision 21 technologies. We are also planning a continuing series of specific, focused workshops for separate technology areas. Each of these workshops will focus on a single Vision 21 technology or on a small group of related technologies, e.g., gasification and gas cleanup. The purpose of the workshops is to provide opportunities for sharing of R&D results, update and refine R&D needs, and maintain industry interest and involvement in the Vision 21 program.

**REFERENCE**

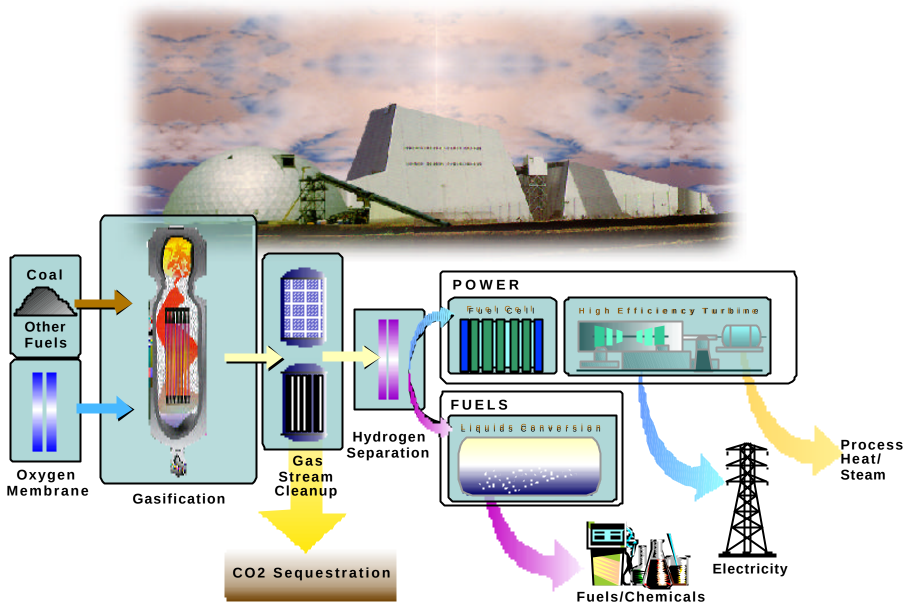
1. "Vision 21, Fossil Fuel Options for the Future," National Research Council, Committee on R&D Opportunities for Advanced Fossil-Fueled Energy Complexes, National Academy Press, Washington,

D.C., 2000.

Table 1. Vision 21 Energy Plant Performance Targets

| | |
|---|---|
| Efficiency-Electricity Generation | 60% for coal-based systems (based on fuel HHV[1]); 75% for natural gas-based systems (LHV[1]) |
| Efficiency-Fuels Only Plant | 75% feedstock utilization efficiency (LHV) when producing fuels such as $H_2$ or liquid transportation fuels alone from coal |
| Environmental | Atmospheric release of:<br>< 0.01 lb/million Btu sulfur and nitrogen oxides, < 0.005 lb/million Btu particulate matter<br>< one-half of emission rates for organic compounds listed in the "Utility HAPS Report"[2]<br>< 1 lb/trillion Btu mercury<br>40-50% reduction of $CO_2$ emissions by efficiency improvement, 100% reduction with sequestration |
| Costs | Aggressive targets for capital and operating costs and RAM[3]; products of Vision 21 plants must be cost-competitive with other energy systems with comparable environmental performance, including specific carbon emissions |
| Timing | Major benefits from improved technologies begin by 2005; designs for most Vision 21 subsystems and modules available by 2012; Vision 21 commercial plant designs available by 2015 |

1. HHV = higher heating value LHV = lower heating value
2. *Study of Hazardous Air Pollutant Emissions from Electric Utility Steam Generation Units - Final Report to Congress,* Volume 2, EPA-453/R-98-004b, 1998
3. Reliability, Availability, and Maintenance


Coal
Other Fuels
Oxygen Membrane
Gasification
Gas Stream Cleanup
CO2 Sequestration
Hydrogen Separation
POWER
Fuel Cell
High Efficiency Turbine
FUELS
Liquids Conversion
Process Heat/ Steam
Electricity
Fuels/Chemicals