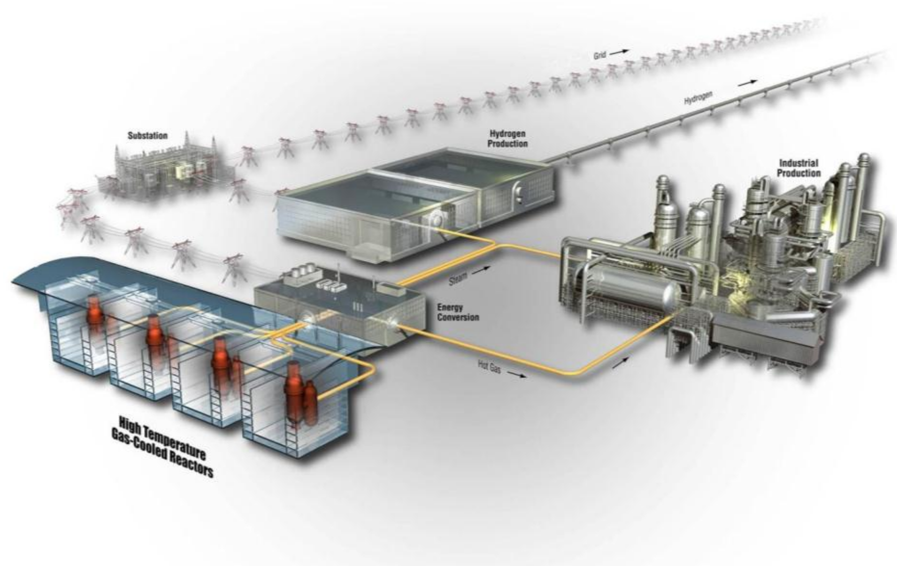
INL/EXT-12-27626

Overview of Energy Development Opportunities for Wyoming

November 2012



University of Wyoming

Wyoming Business Council

NGNP Industry Alliance
Clean Sustainable Energy for the 21st Century

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November 2012

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Idaho Falls, Idaho 83415
http://www.inl.gov

in collaboration with

State of Wyoming
Wyoming Business Council
The University of Wyoming
NGNP Industry Alliance Limited

Prepared for the
Wyoming Business Council
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

ABSTRACT

The State of Wyoming (represented by the Governor's office, the Wyoming Business Council and the University of Wyoming), the NGNP Industry Alliance Limited, and the Idaho National Laboratory have conducted an evaluation of energy development opportunities for Wyoming. The evaluation concludes that deployment of a carbon conversion industry producing synthetic transportation fuels and chemicals can provide a long term and stable market and add considerable value to Wyoming's indigenous coal and natural gas resources with the potential of providing substantive economic benefit to the State. The evaluation also develops a conceptual strategy for transformation of Wyoming's electricity generation from primarily coal fired plants to a diverse mix of generating technologies that provides flexibility in adapting to changes in policy and regulation, and shifts in the energy market. An analysis of hybrid energy systems concludes that hybridization of power generation with synfuels production could be beneficial in Wyoming where it is desired to increase the amount of variable generation technologies (e.g., wind generation) beyond that which can be accommodated by conventional transmission grid controls.

EXECUTIVE SUMMARY

E-1. Evaluations for Wyoming

The State of Wyoming (represented by the Wyoming Business Council and the University of Wyoming), the NGNP Industry Alliance Limited, and the Idaho National Laboratory conducted an evaluation of energy development opportunities for Wyoming. Two evaluation reports were completed[a]. The first evaluation report focuses on the technical and economic viability of alternative carbon conversion processes for producing synthetic transportation fuels and chemicals, and the beneficial uses of nuclear energy (e.g., high temperature gas-cooled reactor [HTGR] technology) to provide the considerable energy needs of a carbon conversion industry and the electric power industry. The second establishes on a preliminary basis the feasibility of dynamically apportioning the thermal energy of nuclear and non-nuclear cogeneration systems and hybrid energy systems between electric power production and process heating for the purposes of producing value-added products and mitigating the variability of wind generation in Wyoming.

- *Energy Development Opportunities for Wyoming* (INL/EXT-12-26732)
- *Preliminary Feasibility of Value-Added Products from Cogeneration and Hybrid Energy Systems in Wyoming* (INL/EXT-12-27249)

Reported herein is an overview of the preceding two reports. The conclusions of these evaluations provide a conceptual foundation upon which Wyoming, in partnership with industry, can develop energy policy and projects for implementation. A growing carbon conversion industry and diverse fossil-renewable-nuclear electric power generating industry can be supported by advanced manufacturing in the State, as well as a service, educational, and product transport infrastructure that support these new industries. These industries provide the opportunity for significant job growth and important contributions to the State's economy.

The feasibility evaluation focuses on applying small modular nuclear reactors which include the HTGR as well as emerging light-water, liquid-metal, and molten-salt cooled nuclear reactor technologies that are being developed by several companies. It also addresses hybrid energy systems concepts that would compensate for the intermittency and variability of wind power generation for generating capacities that exceed the conventional control capabilities of the electric grid, thus enabling better utilization of the vast wind resources in Wyoming. In addition, it compares the relative benefits of natural gas/combined cycle hybrid energy systems with small modular reactor plants.

The potential to increase uranium extraction and the associated supply of uranium and intermediate products in Wyoming was also evaluated. There are limited opportunities to compete in nuclear fuels fabrication in a global economy; however, the production of uranium hexafluoride from yellow cake produced in the State is a potential entry to a larger fuel cycle industry as the growth of nuclear energy increases in the future.

E-2. The Opportunities

Important opportunities exist for the energy future of Wyoming that will:

- Sustain and possibly grow its coal and natural gas industries
- Add substantive value to its indigenous coal, natural gas, and uranium resources, and support expanded use of wind resources

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a Printed and electronic copies are available through the Wyoming Business Council or the Idaho National Laboratory.

- Reduce dramatically the environmental effect of energy production and power generation capability within and outside Wyoming
- Add substantive opportunities to develop an advanced manufacturing industry in the State
- Increase the State's Gross Domestic Product (GDP).

Wyoming has a wealth of primary energy resources in the forms of coal, natural gas, wind, uranium, and oil shale. Most of Wyoming's coal and gas resources are exported from the State in their unprocessed form rather than as more refined, higher value products. Further, important challenges arise from expanding and ever more demanding government environmental requirements whether these resources are used in-State or exported for use elsewhere. Additionally, low natural gas prices have resulted in substantive reductions in severance taxes and based on the commodities futures market are projected to remain low for at least a decade. Wyoming's leadership recognizes the opportunity to broaden the State's economic base by using its energy resources to make value-added products such as synthetic transportation fuels and commodity chemicals. Producing these higher value products in an environmentally responsible manner will require use of clean energy technologies including nuclear energy. These higher value products can be used by Wyoming's populace and industry, and considerably larger quantities exported to regional, national, and international markets.

An industry-State-federal partnership could facilitate research, development and demonstration projects. Collaboration with national laboratories and international institutions can be beneficial. A vibrant work force of thousands of qualified construction workers, trained operators, instrument and controls technicians, skilled maintenance workers, health physicists, and all fields of engineering ranging from environmental to civil, electrical, mechanical, chemical, and nuclear engineers will be required to realize this goal. An advanced manufacturing industry that supports the carbon conversion and nuclear energy industries will be required and will add to Wyoming's GDP to the extent developed within the State.

Regardless of the approach to Wyoming's energy future, the investment decisions made by industry and enabled by Wyoming must be technologically diverse and flexible to allow Wyoming and its industries to adjust to changing global energy realities.

E-3. The Approach

These opportunities can be realized through:

- ***Strengthening the coal and natural gas economy in Wyoming by building a carbon conversion industry***

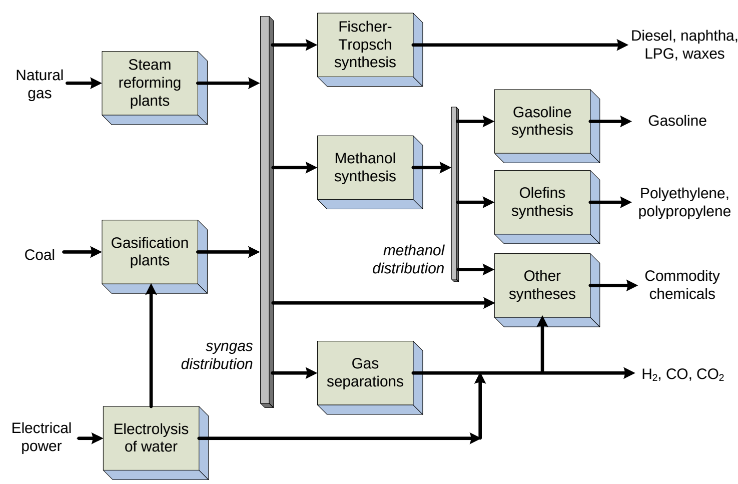
  The two evaluation reports suggest a strategy that promotes development of a substantial carbon conversion industry in Wyoming, beginning with a nominal carbon conversion plant that produces an amount of gasoline that is fungible in the region's fuels market. The analyses indicate the use of nuclear energy could be an important part of addressing anticipated, ever more demanding, environmental requirements while mitigating expected volatile national and international energy pricing. The business case is straightforward:

  - The extraction and utilization of coal is an important part of Wyoming's economy—contributing ~12% of the GDP. Over 95% of the extracted coal is exported from Wyoming, currently providing about 40% of the nation's energy needs—but is not used to directly expand the State's economy. The future of coal is being challenged by changing and ever more demanding environmental requirements for its extraction and use.
  - Over 90% of the natural gas extracted in Wyoming is exported, providing about 9% of the nation's natural gas needs in recent years, contributing ~18% of Wyoming's GDP. However, the

decreased natural gas prices over the last few years necessary to compete with shale gas extracted elsewhere has reduced that contribution. Natural gas commodity futures suggest that the reduced prices may persist for a decade.

New industries are needed that are focused on value-added processes which will retain more of the end-use value of indigenous carbon resources within Wyoming. Strengthening the carbon resource economy by targeting new markets can be achieved through development of a carbon conversion industry for transformation of coal and natural gas to synthetic transportation fuels and chemicals that are the building blocks for the chemical industry. Over the longer term, environmentally clean nuclear energy can provide the substantial energy needs of a carbon conversion industry.

As a far reaching example, notionally redirecting the current Wyoming coal production to making synthetic fuels (e.g., gasoline or diesel) could supply over 50% of the current total U.S. consumption of liquid hydrocarbon fuels—at prices competitive with traditional refining processes. However, the capital investment to achieve this capability would be substantial. Practically carving out the achievable part of this possible energy future requires developing a far-sighted partnership with industry, starting with an incremental strategy that can set Wyoming on the path to becoming a major player in an environmentally responsible carbon conversion industry and in deployment of next generation nuclear energy technology.



Entry into a carbon conversion industry can be phased through construction of process facilities using conventional technologies that can be operational within the next decade focused initially on producing transportation fuels (e.g., coal-to-liquids or natural gas-to-liquids facilities to produce gasoline). Eventually, expansion of a carbon conversion industry potentially using the distributed process model shown at right can be realized. The design of carbon conversion facilities should be intentionally compatible with integration of nuclear energy technology[b]. Because the commercialization of new nuclear energy technology is expected to extend over the next 10 to 25 years, a notional strategy would be to deploy carbon conversion facilities using conventional processes in the short term and anticipate incorporation of the nuclear reactors over the longer term. Nuclear energy integration will result in the greatest environmental benefits while providing a reliable, stable cost of energy for several decades of operation.

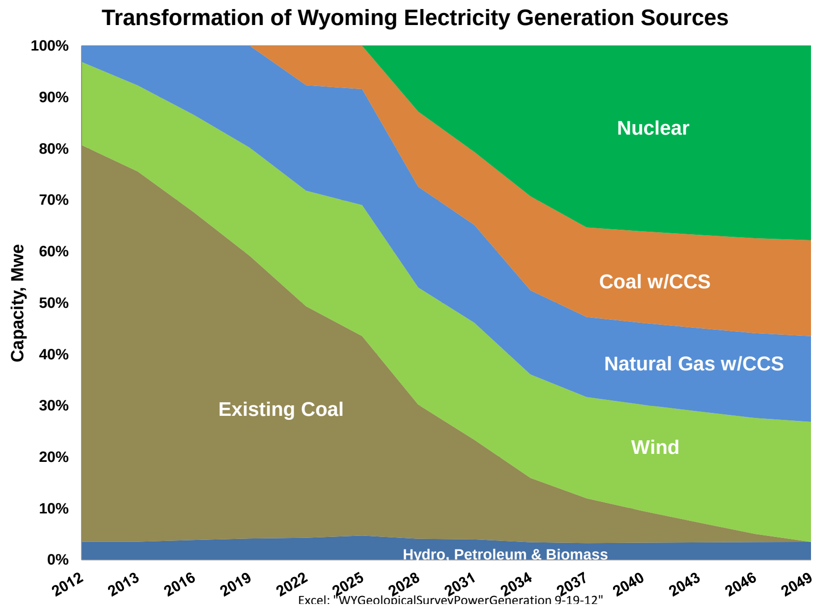
- ***Ensuring continued reliable and affordable sources of energy for Wyoming's industries and people by diversifying the technologies for generating electric power***

  Today, over 95% of Wyoming's electricity is generated by burning coal with a delivered electric power price that is among the lowest in the United States. Anticipated environmental requirements for greenhouse gas emissions necessitate looking at alternative forms of energy production, and in particular electric power generation. Further, managing the anticipated future mix of energy

b Nuclear energy provides an environmentally responsible source of energy that addresses anticipated carbon constraining regulatory requirements. Further, nuclear energy mitigates the effects of volatile fossil fuel energy pricing. HTGR nuclear energy technology provides highly efficient generation of electricity and high temperature process heat that fulfills the requirements of process plants.

production methods, some of which are highly variable such as wind generated electricity, may involve adopting hybrid energy system approaches building on the experience with mixed energy production systems elsewhere.

The anticipated retirement over the next several decades of Wyoming's aging coal-fired electric power generating fleet—both a challenge and an opportunity—requires long range planning to ensure that the replacement power generating technologies fulfill the desired or policy-imposed business and environmental requirements. Selecting a diverse set of replacement power generating technologies is warranted, considering the uncertainties inherent in predicting future energy resources and demand, both nationally and internationally. The figure at the right shows a notional strategy for replacement of existing coal-fired generation. Best available information suggests that the transformation to this diverse set of technologies should initially include natural gas combined cycle generation and renewables, subsequently complemented by clean coal technologies and nuclear energy—the mix primarily determined by:



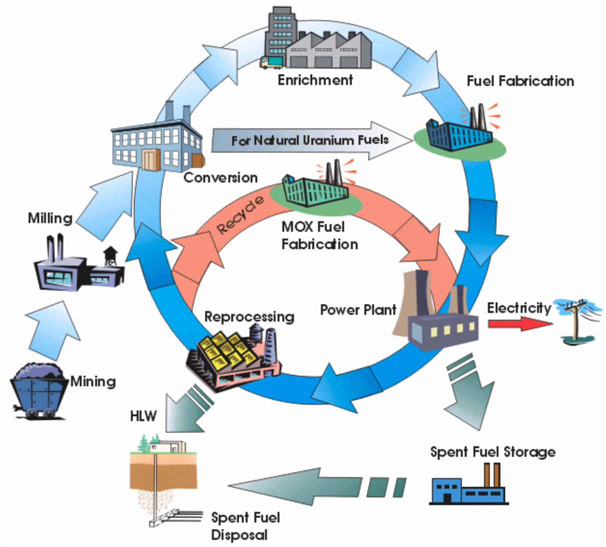
- Anticipated national and international energy price trends,
- Wyoming's long term industrial base,
- Extent of desired energy self-sufficiency, and
- Wyoming's energy export posture.

A diverse technology mix will allow Wyoming and its industries to adjust to evolving global energy realities.

Wyoming has an abundance of wind generation potential that has not been fully exploited. As part of identifying approaches to address better utilization of this wind generation potential, energy system hybridization has been evaluated to increase the value of wind generation to the State through, for example, supporting production of value-added products or increasing exports of this renewable power to neighboring states with Renewable Portfolio Standards. This could be accomplished by increasing the percentage of wind generation on the grid. By its nature, however, wind generation is variable and intermittent, varying with the speed of wind. Conventional electric grid control schemes can mitigate this variability for a limited amount of wind generation on the system; a typical value is up to ~25% of total installed capacity. If wind generation is increased above this value hybrid energy systems may be more economic in mitigating the effects of increases in wind generation capacity than augmenting the conventional grid control schemes. Depending on the scope of generation and export, this could require, however, upgrading or adding to transmission system capacity in Wyoming and in neighboring states and wide ranging proliferation of wind turbines throughout the State. Extensive implementation of these actions may not be consistent with Wyoming's concept of land and resource use. An alternative use of wind generation is to power specific applications, (e.g., production of oxygen) without connection to the grid. This eliminates the challenges to grid operation and would locate the wind turbines in areas already designated as or used for industrial purposes. Use of hybrid energy systems to support the production of value-added products has been evaluated and several reference cases are described using non-nuclear and nuclear hybrid system configurations.

- ***Capitalizing on anticipated growth of the nuclear energy industry by producing higher-value products from uranium***[c]

  Wyoming produces a large fraction of the country's uranium and currently exports it as yellowcake which is processed elsewhere for use as nuclear reactor fuel as shown in the figure to the right. The immediate next stage of processing, conversion to uranium hexafluoride, could be accomplished in Wyoming, providing considerable value-added. A separate evaluation of the economic viability of this approach should be undertaken with representatives of the fuel cycle industry considering both the domestic and foreign long term market.

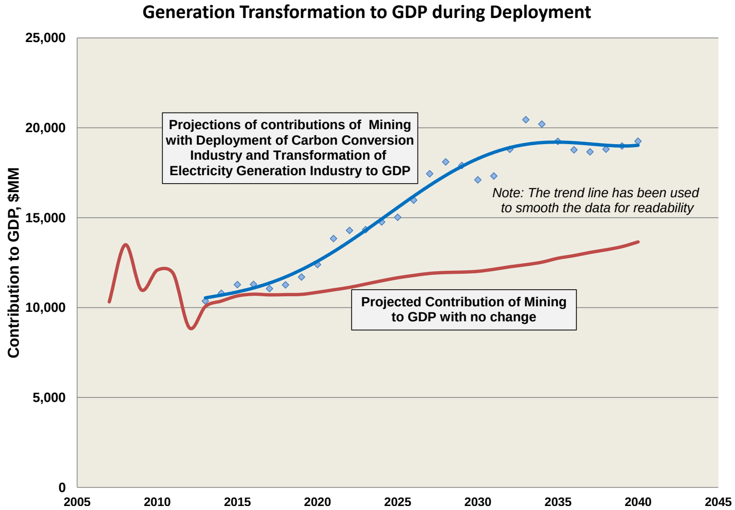


E-4. The Result

Initiating the carbon conversion industry and diversifying the electric power industry as described earlier are estimated to have the effect shown in the figure on the GDP for Wyoming compared to continuing the status quo. These results are derived using a notional model for Wyoming's energy future described in the above referenced reports. The figure does not consider even larger effects of more rapid growth of a carbon conversion industry or value-added from expansion of uranium mining and processing and build-out of the wind generation industry.

These initiatives include a capital investment of ~$14B (2011$) to build-out 200,000 bpd of carbon conversion for synfuels production that could provide approximately ~$7B (2011$) of annual revenue. With the development of product delivery pipelines to distant markets, this volume could be increased to a level that rivals the imports from several foreign countries. The opportunity to effect a $100B investment over 20 to 30 years would solidify Wyoming's position as an energy producing State with a vibrant economy. It's a prize that few states have the opportunity to develop.

Total Contribution of Carbon Conversion Industry and Electricity Generation Transformation to GDP during Deployment



c The fuel cycle representation is from the International Atomic Energy Agency's Nuclear Fuel Cycle Information System website; http://infcis.iaea.org/

E-5. The Next Steps

The suggested approaches to Wyoming's energy future are bold. However, the transformation and growth can be achieved in phases that can be accommodated by industry and Wyoming with the opportunity to adjust direction as Wyoming's energy future matures and becomes clearer. The following provide suggested near term steps that can put Wyoming on the road to an energy, industry, and economic transformation.

- *Establish forward-looking partnerships between industry and Wyoming that are used to establish mutual goals and success criteria*. Such partnerships would include existing Wyoming industry as well as new industries that will invest in energy and processing technologies. The public-private partnerships' goals and success criteria can address use of indigenous resources, economic figures-of-merit that measure progress and address both the needs of the State and industry, approaches to reducing regulatory burden, incentives that attract investment, and approaches that reduce investment uncertainty and risk.
- *Establish a multi-decade State energy policy that codifies Wyoming's vision and plan for transforming its energy industry and developing its industrial and educational infrastructure*. Such policy codifying the strategy and plan for transformation provides a backdrop against which industry investment can be made with reduced business risk and provides a benchmark against which necessary course corrections can be recognized.
- *Establish a statutory State agency that provides the ongoing leadership for Wyoming's energy transformation*. Industry evaluates the market and chooses the technological approaches for achieving the goals of Wyoming's energy policy. An empowered State agency is necessary to guide industry on the path to transformation, provide a clearing house for implementation of the State's energy policy and assist in removing roadblocks that will be encountered at the State and federal level.
- *Actively support State, regional and national initiatives, both in industry and government, which will enable the success of Wyoming's energy transformation*. This could take the form of supporting industry and federal activities that will commercialize energy technologies such as next generation nuclear energy technologies, transmission system expansion and innovation, and commercialization of cogeneration and hybrid energy technologies. More specifically, as examples:
    - Via energy policy, indicate that Wyoming is interested in hosting first-of-a-kind facilities using next generation nuclear energy technology, cogeneration, and hybrid energy system concepts to support the growth of its carbon conversion industry and transform its electric power generation industry
    - Actively support industry's commercialization efforts for next generation nuclear energy technologies (e.g., HTGRs and other small modular reactors) and other enabling technologies (e.g., high temperature steam electrolysis for hydrogen and oxygen production) that can contribute substantially to the success of Wyoming's carbon conversion industry
    - Engage the DOE National Laboratories to leverage the intellectual capacity, simulation tools, and testing and development investments designed to address challenging research and development problems. Federal/State/Industry collaboration can accelerate analysis and assessments that may help define and optimize energy system architectures. Government and industry partnerships may also be key to providing incentives that can overcome specific market barriers, including for example, regulatory barriers. National Laboratories can facilitate international cooperation through approved Protocol Agreements that can help accelerate nuclear energy technology and cogeneration and hybrid energy system demonstration and deployment experience. Finally, National Laboratories can enhance education and workforce training through research internships and visiting faculty programs.

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Overview of Energy Development Opportunities for Wyoming

1. DEVELOPMENT APPROACHES FOR WYOMING AND THE PATH FORWARD

Wyoming has a wealth of primary energy resources in the forms of coal, natural gas, wind, uranium, and oil shale. Most of Wyoming's coal and gas resources are exported from the State in their native form rather than as more refined, higher value products. Possible future restrictions on emissions, such as the greenhouse gas CO_2, present a significant challenge to the ongoing use of Wyoming's coal, gas, and petroleum resources both in-State and elsewhere. Current low natural gas prices have resulted in significant reduction in the tax revenue of Wyoming. The commodity futures market indicates that these low prices are likely to continue for at least the next decade. Wyoming's leadership recognizes the need to broaden the State's economic base by increasing the worth of its energy resources by producing value-added products and stabilizing the volatility of energy prices. Through the approaches described below, there are important opportunities for the energy future of Wyoming that will:

- Sustain and possibly grow its coal and natural gas industries
- Add substantive value to its indigenous coal, natural gas, and uranium resources, and support expanded use of wind resources
- Reduce dramatically the environmental effect of energy production and power generation capability within and outside Wyoming
- Add substantive opportunities to develop an advanced manufacturing industry in the State
- Increase the State's Gross Domestic Product (GDP).

1.1 Energy Development Approaches for Wyoming

The opportunities for Wyoming's energy future can be achieved through the following:

- *Strengthening the coal and natural gas economy in Wyoming by building a carbon conversion industry* – A carbon conversion industry will add substantive value to Wyoming's major indigenous carbon resources—coal and natural gas. Carbon conversion will produce high value synthetic transportation fuels and chemicals that form the building blocks for the chemical industry. Over the longer term, environmentally clean nuclear energy (e.g., high temperature gas-cooled reactors and other small modular reactors) can provide the substantial energy needs of the carbon conversion industry and help to stabilize volatile energy prices.
- *Ensuring continued reliable and affordable sources of energy for Wyoming's industries and people by diversifying the technologies for generating electric power* – Anticipated increased environmental requirements necessitate looking at alternative forms of energy production, and in particular electric power generation. A diverse mix of power production technologies (e.g., nuclear energy, clean coal and natural gas technologies, wind generation) is warranted considering the uncertainties inherent in predicting future energy resources and demand. Further, managing the anticipated future mix of energy production resources, some of which are highly variable such as wind generation, may involve adopting hybrid energy systems approaches building on the electric grid control experience with mixed energy production systems elsewhere.

- *Capitalizing on anticipated growth of the nuclear energy industry by producing higher-value products from uranium* – Converting the yellowcake currently produced by Wyoming to uranium hexafluoride can provide considerable value added.

As part of ongoing activities to investigate these approaches, the Wyoming Business Council, representing the State's interests, has participated in collaborative evaluations of energy development opportunities with the NGNP Industry Alliance (an industry consortium), the University of Wyoming, and the U.S. Department of Energy's Idaho National Laboratory. This report summarizes the results of these evaluations to identify:

- Technically and economically viable methods to increase the value added to the economy associated with the extraction and processing of indigenous resources including coal, natural gas and uranium
- Opportunities for application of nuclear energy technologies as part of the overall energy mix. Nuclear energy provides an option that is environmentally clean and provides stable, competitive energy prices.
- Industrial infrastructure capabilities and needs that support the long term energy future.

Two scopes of work were completed in support of these collaborative evaluations. The results, conclusions and recommendations of this work are summarized in two reports:

- *Energy Development Opportunities for Wyoming* (INL/EXT-12-26732)
- *Preliminary Feasibility of Value-Added Products from Cogeneration and Hybrid Energy Systems in Wyoming* (INL/EXT-12-27249).

This report provides a comprehensive but condensed overview of the results, conclusions and recommendations of these two reports.

1.2 Suggested Overall Path Forward

The report, *Energy Development Opportunities for Wyoming* (INL/EXT-12-26732), provides a suggested path forward for Wyoming to pursue a carbon conversion industry as a central feature improving the value of indigenous resources to the overall State economy with nuclear energy providing the primary source of energy and part of achieving a diverse mix of power generating technologies to replace retiring conventional coal-fired generation. Summarizing:

- Pursue developing a collaborative partnership with industry to build the initial portions of a carbon conversion industry. This collaborative partnership will include planning for the initial carbon conversion process(es) to be deployed, the site(s) selection and the overall approach to building-out the carbon conversion industry based on best available projections of the market for the products to be produced and a plan to develop infrastructure to deliver these products to both regional and distant markets.
- In the planning basis for a carbon conversion industry, ensure that economically competitive and environmentally compatible process plant design configurations are chosen that support a phased approach to integrating nuclear energy technology as the long term source of energy.
- Prepare a plan that anticipates retirement of portions of the current coal-fired power generation fleet (e.g., considering age and evolving regulations), modification of other portions of the current fleet for carbon capture and storage and/or use in enhanced oil recovery applications, continued increases in renewable generation capabilities and the deployment of nuclear energy technologies for base load capabilities. A notional basis for such planning is provided and requires looking ahead for management of the future energy mix using techniques such as those utilized in hybrid energy systems. An essential decision is the extent to which Wyoming and its power generation industry plan

to continue to be a net exporter of energy in the form of electricity considering tradeoffs such as investments in new generating capacity and increased transmission system capacity.

- Prepare a plan for industrial infrastructure development based on the needs of a growing carbon conversion industry and in the future, a nuclear energy industry. This includes State regulatory and educational institution changes that will be required.
- Prepare an evaluation of the overall effect on the economy and demographics in Wyoming as these industrial capabilities are realized.

2. CONCLUSIONS

2.1 A Carbon Conversion Industry Can Add Substantive Value to the Wyoming Economy

Wyoming's coal and natural gas economy can be substantively strengthened through development of a carbon conversion industry that comprises multiple facilities applying a variety of processes for conversion of coal and natural gas to synthetic transportation fuels, chemical feedstock and chemicals that are the building blocks for the chemical industry.

The notional configuration of such an industry summarized below can provide substantive increases in the value-added to these indigenous resources, with a corresponding improvement in the Wyoming GDP.

In summary, this industry as notionally described will:

- Provide >$7B (2011$) annual revenue increase
- Increase projected long term mining contribution to GDP by ~$6B (2011$) per annum
- Consume 6.6 million tons of coal (~2% of 2011 production) and 424 billion cuft of natural gas (~20% of 2011 production) each year
- Add a substantive number of jobs and revenue to the State during deployment
- Create 3,200 high-quality permanent jobs.

2.1.1 Entry into a Carbon Conversion Industry Can be through a Phased Approach

The phased approach includes:

- Industry building one or more initial carbon conversion process plants that present a viable business case, and over the longer term expanding the capacity and number of process plants as supported by the market strategy to maintain and grow the State's economy. These plants can use coal or natural gas as the feedstock producing synthetic transportation fuels, chemical feedstock and chemicals
- Integrating nuclear energy as the primary source for process operations as environmental requirements and energy price volatility demand.
- Developing product delivery pipelines into regional and distance markets commensurate with expanding the size of the carbon conversion industry.

To provide a perspective on the scope of work, costs, revenue and economic effects of a carbon conversion industry on Wyoming economy, a notional strategy was developed for deploying such an industry in Wyoming. This notional strategy includes an industry comprised of four different process plants converting coal and natural gas to synthetic transportation fuels. This is the minimum size industry that is judged required to achieve a substantive contribution to the economy. This strategy also includes integration of nuclear energy to supply heat and electricity to these processes over the longer term; including application of both high temperature gas-cooled reactor (HTGR) and small modular light water reactor technologies. The integration of nuclear energy in these processes minimizes greenhouse gas emissions and ensures long term stable energy costs.

Clearly, the selection of the specific process(es) used in the initial plant and in the deployment of an expanded carbon conversion industry within Wyoming will be the responsibility of the owners of the plants. These selections will be made after consideration of several factors including market conditions, energy costs, (e.g., crude oil, coal, natural gas), plant costs, financing, site characteristics including feedstock supply, infrastructure, and the distribution network. The evaluations summarized herein provide some insight into the influence of these factors on the selection of process plant concepts.

These evaluations conclude that plants using either coal or natural gas as feedstock producing synthetic fuels, feedstock or chemicals are technically and economically viable alternatives for developing a carbon conversion industry. For the purposes of this notional analysis two process plants for producing gasoline are selected, one using coal as the primary feedstock and natural gas to generate hydrogen using the steam methane reforming process, and the other using natural gas as the primary feedstock. The analyses completed in evaluating these process plants illustrate the scope of work, costs, schedule, effects on the economy and potential integration with HTGR technology of each of these plant configurations. Both of these plants first produce methanol and then gasoline using the methanol to gasoline process.

Either or both of these process plants configurations are judged to be a prudent early choice for deployment.

- A carbon conversion industry can add value to the State's economy by producing products that have higher value than the feedstock. For example, the coal to gasoline plant discussed herein uses ~$730M of coal and natural gas to produce gasoline and liquid petroleum gas with a market value of ~$2,100M. Similarly, a smaller natural gas to gasoline plant uses ~$520M of natural gas to produce the same products with a market value of ~$1,200M (all 2011$).
- A carbon conversion industry can mitigate the loss of State revenue from coal and natural gas severance taxes by providing alternative markets and revenue streams for these indigenous natural resources.
- These carbon conversion processes are competitive with crude oil refining over a range of crude oil prices from $47 to $100/bbl for natural gas prices ranging from $4/MSCF to $10/MSCF and coal prices ranging from $10 to $50/ton. Crude oil prices and natural gas prices have been in these ranges over the last decade and are projected to continue to be in these ranges over the long term.
- These alternatives are well developed processes using commercially available components and hence could be deployed as soon as an Owner and funding are identified.
- The methanol process can also be used to produce chemicals used as building blocks in the chemical industry providing flexibility to maintain plant economic viability in changing market conditions. For example, a coal conversion plant based on the methanol process uses ~$165M of coal to produce olefins with a market value of $1,300M. (All 2011$)

Presuming the necessary industry investment, the initial phase of a carbon conversion plant could be operational by 2017. The total plant could be at full capacity by 2020 as shown in Figure 1.

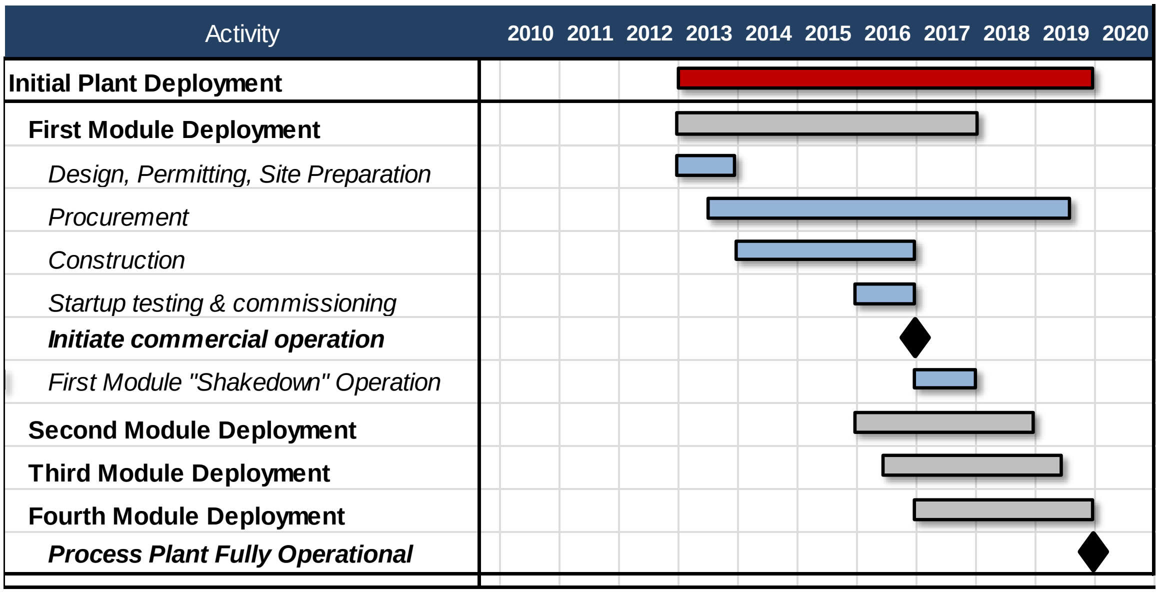


Figure 1. Notional schedule for deployment of an initial carbon conversion industry process plant.

2.1.1.1 Coal and Natural Gas Conversion to Gasoline –Typical Examples of Carbon Conversion Processes

Table 1 summarizes the principal characteristics of representative coal and natural gas to gasoline processes. Each of the plants would be comprised of four modular trains; each train with capacity equal to 25% of the total plant capacity. The module sizes are selected based on conventional equipment sizing. As shown in Figure 1 the modules would be deployed in phases so the plant would startup with 25% capacity and increase to full capacity over a two year period.

The principal differences in the two plants are the first costs and the quantities of gasoline and liquefied petroleum gas (LPG) produced; the coal fed plant higher in both cases. Both processes provide similar value multipliers in the range of 3 to 9 depending on the prices of natural gas and coal and are competitive with refined products at the lower end of Energy Information Administration (EIA) projected crude oil prices over the long term (through 2035; see INL/EXT-12-26732 for a discussion of these projections). Each plant is comprised of four trains to achieve a capacity that provides a return on investment typical of the petrochemical industries, (e.g., 10 to 15% after taxes).

Table 1. Principal characteristics of coal and natural gas to gasoline plants.

Plant	Coal Usage (tons/day)	Natural Gas Usage (MSCF/day)	Gasoline Produced (bpd)	LPG Produced (bpd)	Cost ($M)	Annual Revenue ($M)	Equivalent Crude Oil Price ($/bbl)
Coal to Gasoline with SMR	12,000	290	58,000	9,000	5,900	2,100	72
Natural Gas to Gasoline	N/A	290	33,000	5,300	1,900	1,200	58

These carbon conversion plants will compete for market share with crude oil refineries. The production costs of products refined from crude oil are a strong function of the price of crude oil; see Figure 2. Also shown on this figure is the increase in refinery production costs projected for a $50/ton cost of CO_2. As shown this effect is small because the CO_2 emission per barrel of gasoline is relatively low (~96 KgCO_2 eq/bbl of gasoline refined). This figure also compares the projected production costs for a coal to gasoline plant with a steam methane reformer hydrogen supply for variations in natural gas price and CO_2 costs from $0 to $50/ton

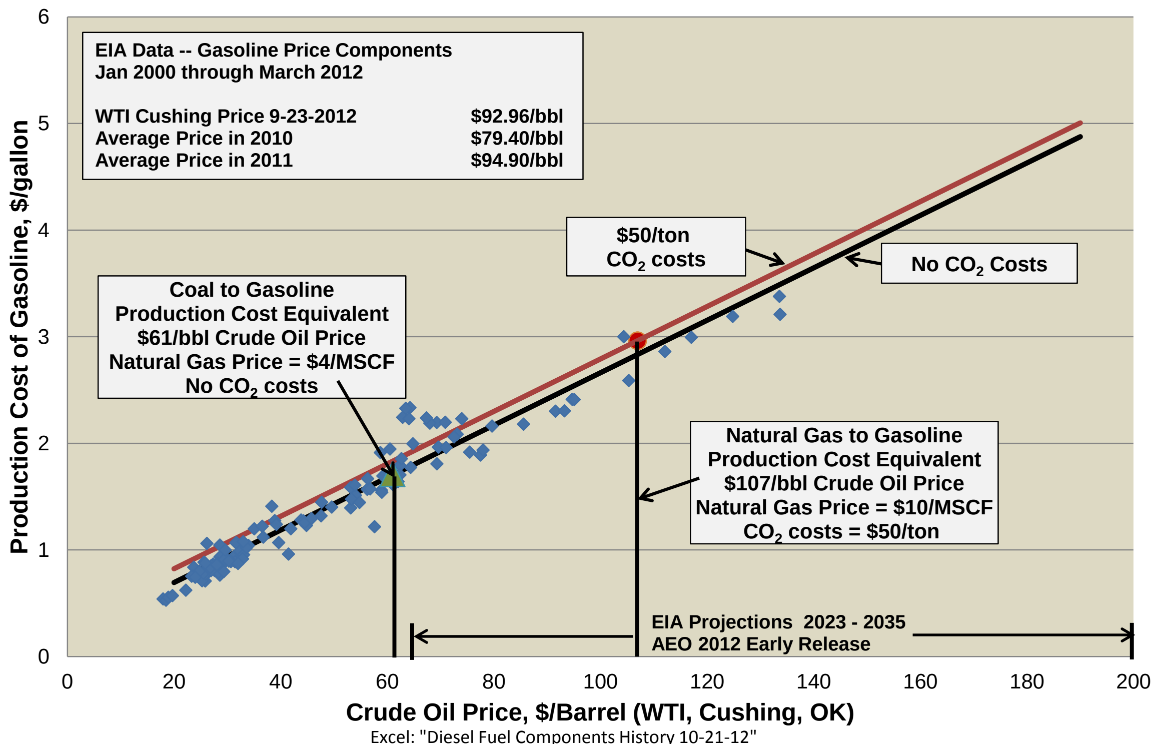


Figure 2. Coal to gasoline production cost compared with costs for refined gasoline versus crude oil price, costs of co_2 and price of natural gas.

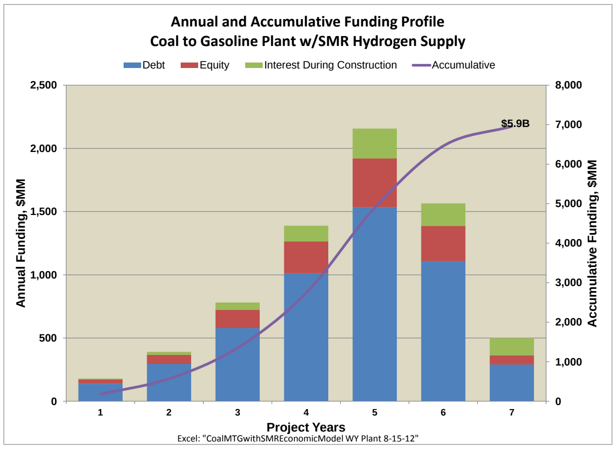
Review of Table 1 and Figure 2 shows:

- $50/ton CO_2 cost has a modest effect on gasoline production cost refined from crude oil; equivalent to an increase of ~$5.30/bbl in crude oil price.
- $50/ton CO_2 cost has minimal effect on production cost of gasoline converted from coal and natural gas; ~$0.11/gal.
- An increase in natural gas price from $4/MSCF to $10/MSCF results in a production cost for gasoline converted from coal and natural gas within the mid- range of projected crude oil prices, (equivalent to ~$107/bbl).
- A natural gas price of ~$10/MSCF is at the upper end of projected long term prices to the industrial user. These projections are developed in Appendix E of *Energy Development Opportunities for Wyoming* (INL/EXT-12-26732). The projections incorporate the range of EIA projections of natural gas prices through 2035 combined with assessments of the impact of increased use of natural gas for electricity generation in the U.S. and increasing exports on these prices. These assessments project a potential range of natural gas prices in 2035 from ~$7/MMBtu to ~$10/MMBtu.

2.1.1.2 Deployment of the Notional Coal to Gasoline Plant in Wyoming will Provide Economic Benefit and Create Jobs

Figure 3 summarizes the annual and cumulative investment and jobs (man-years) required to complete design, construction and commissioning of a coal to gasoline plant. This investment and the associated jobs will have positive impact on the Wyoming economy through increased revenue and GDP. The operation of the plant provides economic benefits over the long term. In summary:

- At least 70% of construction costs would be expended in Wyoming, (e.g., labor and materials).
- ~$4B (2011$) of the construction costs would contribute directly to the State's GDP over the construction period. During operation the plant would derive ~$2B in annual income that will result in increased tax revenues for the State in addition to the coal and natural gas severance taxes
- Coal and natural gas consumption as feedstock in a carbon conversion industry will provide a stable long term demand for Wyoming natural resources.
- 400 permanent jobs would be created to operate the plant.
- The revenue and jobs would be beneficial to Local and State economies.



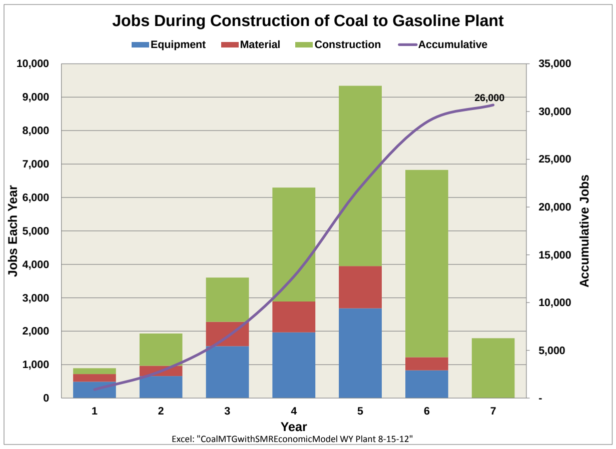


Figure 3. Required investment and jobs for deployment of the initial coal to gasoline process plant.

2.1.2 Expansion of the Number of Plants can Provide Substantive Economic Benefit

In summary this notional expansion would entail:

- Four plants producing 200,000 bpd of synthetic transportation fuels and chemical feedstock
- $7B (2011$) per year revenue from the fully deployed industry
- Regional, national and international distribution potential
- Distributed facilities across the State to take advantage of favorable infrastructure and to address specific areas needing economic development
- Potential for expansion as market conditions and State objectives dictate.

This notional four plant carbon conversion industry has been evaluated to provide perspective on costs, schedule, coal and natural gas consumption and revenues for its deployment. Plants using both coal and natural gas as feedstock have been assessed to illustrate the characteristics of each as shown in Table 2.

Table 2. Performance characteristics of the carbon conversion industry plants.

Type	Capacity (bpd)	Products	Natural Gas Consumption (MMSCFD)	Coal Consumption (short tons per day)	Cost, $M (2011$)	Annual Revenue $M (2011$)
Natural Gas to Gasoline (GTG)	40,000	Gasoline & LPG	290	—	2,200	1,050
Natural Gas to Liquids (GTL)	50,000	Diesel, Naphtha & LPG	430	—	2,400	1,860
Coal to Gasoline (CTG)	60,000	Gasoline & LPG	290	11,845	5,900	2,100
Coal to Liquids (CTL)	50,000	Diesel, Naphtha & LPG	280	7,720	3,900	1,860
Totals	200,000		1,290	19,565	14,100	6,870

In addition to the annual revenue generated by these plants, the periods of construction add substantial amounts to the economy and the State's GDP as shown in Figures 4 and 5.

Figure 4 shows the expenditure profile and the revenue profile for the process plants. A period of ~25 years was used for the full deployment to spread the costs. The costs of deployment are estimated at ~$14.1B with a peak annual expenditure of ~$1.8B. Annual revenue of ~$6.9B is achieved upon full deployment of the industry. This is estimated to contribute ~$5.5B of gross value added to the State's GDP. Both of these provide substantive benefit to the State's economy. (All 2011$)

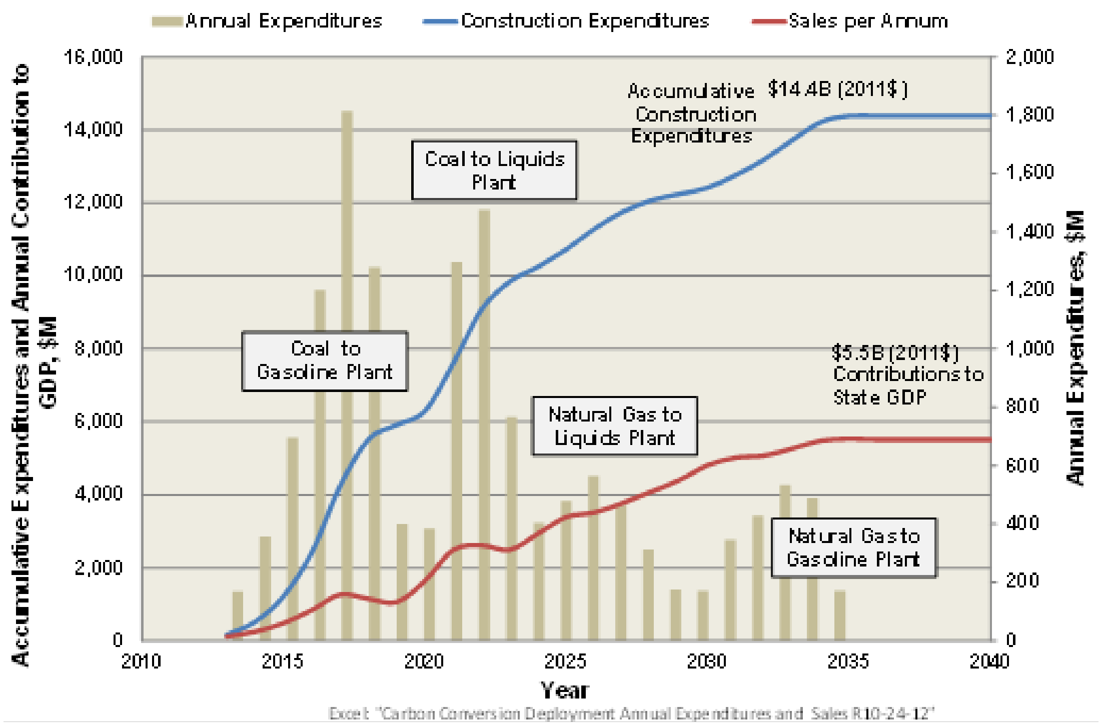


Figure 4. Annual and accumulative expenditures and annual contribution to the State's GDP for deployment of the carbon conversion industry.

Figure 5 provides a perspective from Wyoming's view on the potential benefits of the carbon conversion industry by comparing the projected State GDP for (1) continuing with current coal and natural gas exports and in-State use, with (2) developing a carbon conversion industry and the resulting value-added products. There are important assumptions and uncertainties in developing this figure. However, such overall predictions, even if uncertain, are important in gaining an approximate understanding of the course to pursue.

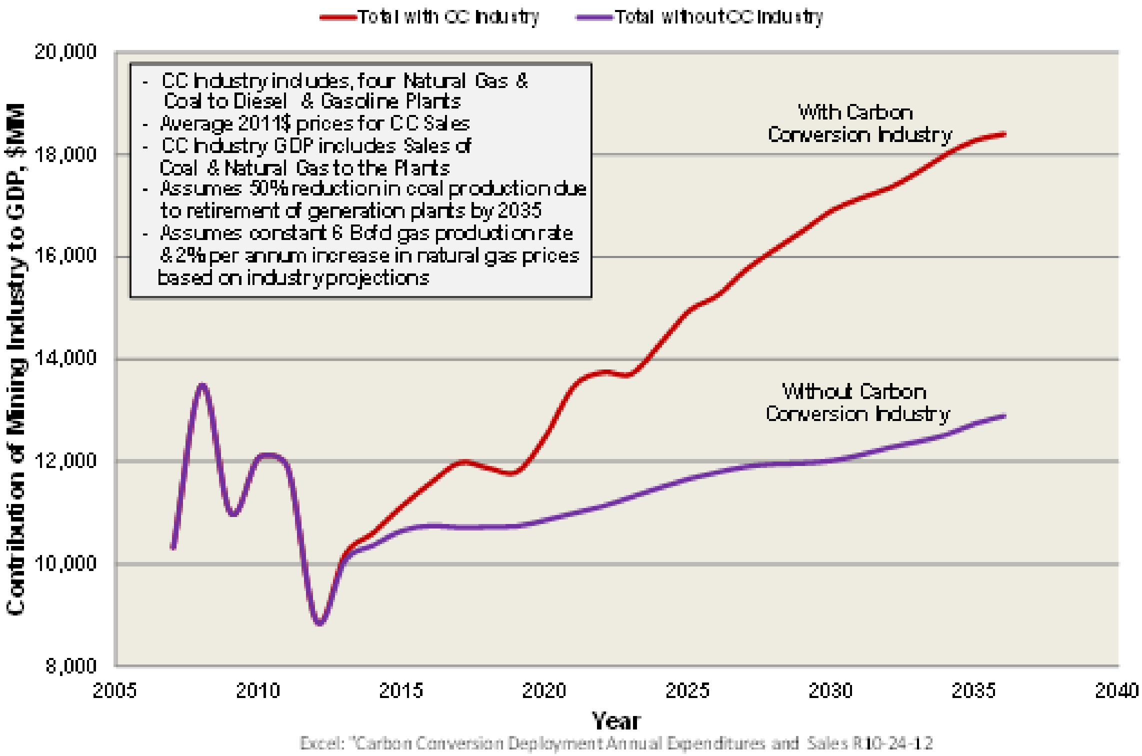


Figure 5. Comparison of mining industry contributions to GDP with and without carbon conversion industry deployment.

2.1.3 An Option—A Distributed Carbon Conversion Industry Configuration

Multiple facilities distributed throughout Wyoming fulfilling the several stages of processing may have benefit in taking advantage of the area's unique feedstock supply, infrastructure, labor force, local interest and distribution access to national and international markets

Many (but not all) coal and natural gas conversion processes have an initial step of converting those indigenous carbon resources into synthesis gas, a mixture of hydrogen and carbon monoxide, which is then further converted to the desired products. When several plants in this industry are established, it would be feasible for them to develop an integrated syngas exchange network for operational backup, to allow the synthesis of small amounts of specialty products using another plant's possible excess syngas production capacity, and to allow companies to begin specializing in either the conversion of the primary carbon resource or the production and sales of commodity and specialty fuels and chemicals. This integrated structure, illustrated in Figure 6, is similar to a petrochemicals industry configuration.

One of the chemical products could be methanol, an important commodity chemical that also can be further converted to many other chemicals and plastics. This variety of uses could lead to a second regional intermediate product distribution network specifically for it.

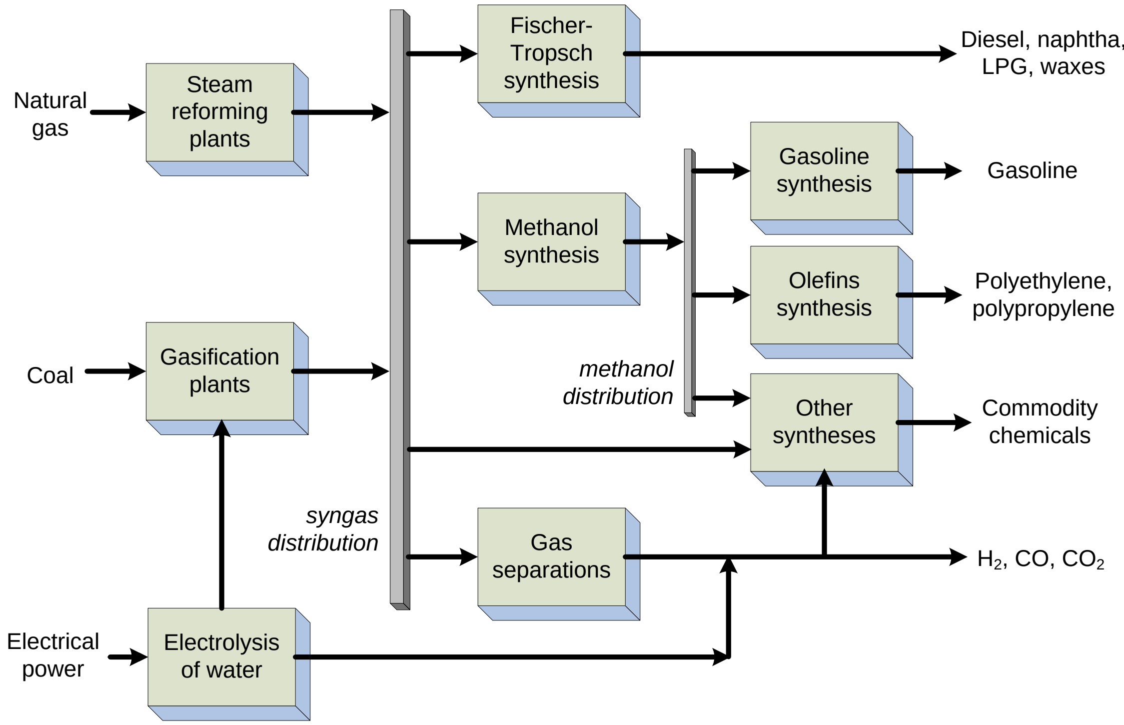


Figure 6. Distributed carbon conversion industry concept.

This approach allows a variety of products to be made at scale to match market needs because there is no need to build the front end to make syngas or methanol. This approach also provides greater flexibility if product markets change. If, for example, in the long term gasoline is no longer needed in large amounts for the light vehicle fleet, other fuel or chemical products could be made from the former feed of syngas. Depending on the old and new processes, it is plausible that the old synthesis plant need not be scrapped but only converted to make the new product.

2.1.4 Integration of Nuclear Energy In the Carbon Conversion Industry Provides Environmentally Clean Energy at a Long Term Stable Price

Integration of nuclear energy in the forms of High Temperature Gas-cooled Reactors (HTGR) and Small Modular Reactors with the carbon conversion processes has several benefits:

- Reduces CO_2 emissions by 65% to 95%
- Provides long term stable energy costs
- Increases the efficiency of converting carbon to fuel up to 95%
- In a hybrid configuration has the potential of offsetting the variability of wind generation
- Water consumption can be significantly reduced by power that can be generated using thermally more efficient high temperature reactor technology (e.g., HTGRs).

2.1.4.1 Integration of HTGR Technology with Carbon Conversion Processes

The HTGR technology will be available for commercial operation in the mid-to-late-2020s. For the notional deployment schedule in Figure 7, this technology could be back fit to the first two plants and incorporated in the construction of the third and fourth plants. Table 3 summarizes the characteristics of the HTGR plants and Figure 8 shows the effect of this integration on the expenditure profile for

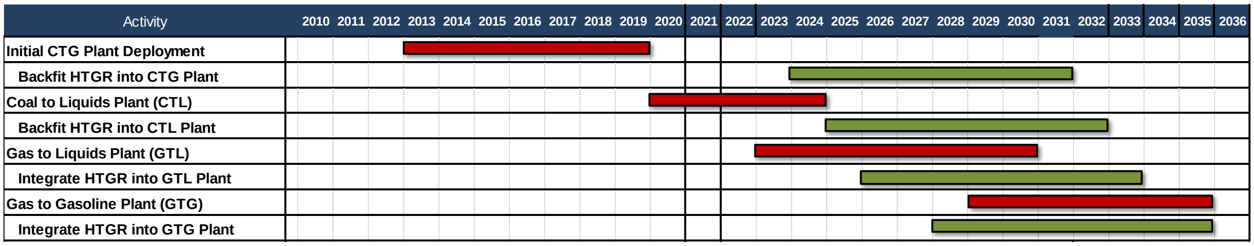


Figure 7. Notional schedule for deployment of the carbon conversion industry.

Table 3. Characteristics of the HTGR plants integrated with the process plants.

Integrated with	Thermal Capacity MW(t)	Number of Modules	Heat Supply to Process MW(t)	Electricity to Process MW(e)	Electricity to the Grid MW(e)
Natural Gas to Gasoline (GTG)	3,000	5	387	115	963
Natural Gas to Liquids (GTL)	3,000	5	479	0	1038
Coal to Gasoline (CTG)	3,000	5	1112	60	706
Coal to Liquids (CTL)	3,000	5	1201	91	637
Totals	12,000	20	3,179	266	3,344

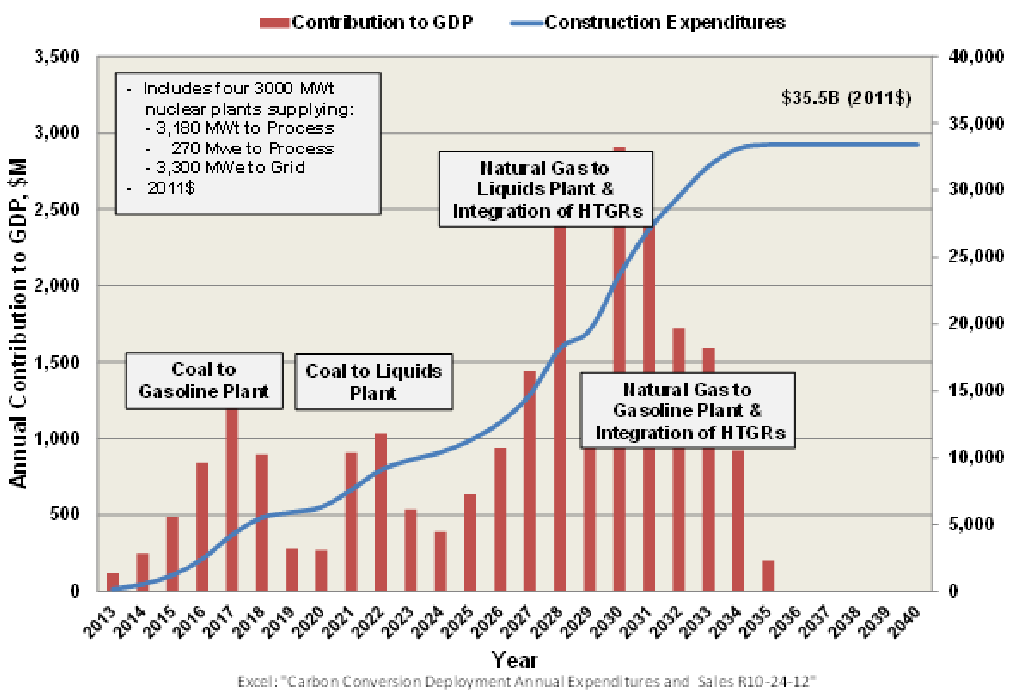


Figure 8. Total expenditures and contributions to GDP from integration of HTGR in the carbon conversion processes.

deployment of the carbon conversion industry and the contribution of these expenditures to the Wyoming GDP. This contribution to the GDP would be in addition to that of the deployment and operation of the carbon conversion industry. In summary these additions:

- Add $20B to the cost of deploying the carbon conversion industry
- Substitute ~3,300 MW(e) of clean nuclear electricity generation for replacement of existing coal based generation as it is retired
- Contribute several hundred million to over $2.5B to the Wyoming annual GDP during deployment.

The choice of nuclear energy technology for use in the carbon conversion processes and for electricity generation depends on the thermodynamics of the processes. Other nuclear technologies could be applied but must be consistent with the required process heat thermodynamic conditions and the economics. For example, HTGRs produce process heat up in the range 750-850 °C. The output of process heat as steam from light water/small modular light water reactors is about 300 °C whereas the operating temperatures of molten-salt and liquid-cooled reactors are 500 °C and above. However, with careful design of heat recovery systems and topping combustion with tail gas and other opportunity fuels, the steam and heat from other small modular reactor technologies could possibly be effectively used to support the carbon conversion processes. The use of small modular light water technology in support of the operation of a natural gas to gasoline plant is developed in the assessment of nuclear-fossil-renewable hybrid energy systems (see *Preliminary Feasibility of Value-Added Energy Products from Cogeneration and Hybrid Energy Systems in Wyoming* [INL/EXT-12-27249]).

2.1.4.2 Application of the Hybrid Energy System Configuration to a Carbon Conversion Plant

The previous discussions focus on the use of electrical power and heat to continuously support the conversion of hydrocarbons to fuels and generation of other products. For example in the case of gasoline production, excess electricity is generated for sale on the regional grid and a CO_2 stream is generated that can be sold for enhanced oil recovery. This type of plant arrangement is often referred to as poly-or cogeneration because more than one product is generated. The notion of system hybridization is a new term that can also apply to polygeneration, especially when there are dynamic shifts between the energy feeds into the systems or in the choice of products that are produced, or both.

Wyoming has an abundance of wind generation potential that has not been fully exploited. As part of identifying approaches to address better utilization of this wind generation potential, the feasibility has been assessed of applying energy system hybridization to increase the value of wind generation to the State through, for example, supporting production of value-added products or increasing exports of this renewable power to neighboring states with Renewable Portfolio Standards (see *Preliminary Feasibility of Value-Added Products from Cogeneration and Hybrid Energy Systems in Wyoming* [INL/EXT-12-27249]). Both of these could be accomplished by increasing the percentage of wind generation on the grid. By its nature, however, wind generation is not constant, varying with the speed of wind. Conventional electric grid control schemes can mitigate this variability for a limited amount of wind generation on the system; a typical value is up to ~25%[d] of total installed capacity. If wind generation is increased above this value, hybrid energy systems may be more economic in mitigating the effects of the increase in wind generation than augmenting the conventional grid control schemes because of the multiple products generated and the ability to dynamically apportion energy delivery among these products. However, depending on the scope of generation increase and export, this could require upgrading or adding to transmission system capacity in Wyoming and in neighboring states and wide

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d This value will vary depending on the mix of generation technologies on the grid, the capacity of the grid control components, the injection point of the renewable generation and many other factors.

ranging proliferation of wind turbines throughout the State. Extensive implementation of these actions may not be consistent with Wyoming's concept of land and resource use.

An alternative use of wind generation is to power specific applications (e.g., production of oxygen) without connection to the grid. This eliminates the potentially disruptive effects on the grid operation and would locate the wind turbines in areas designated as appropriate for or already used for industrial purposes. The use of hybrid energy systems in both of these applications has been evaluated and several reference cases are described using non-nuclear and nuclear hybrid system configurations (see INL/EXT-12-27249, above).

Figure 9 depicts one example out of many possible configurations of applying a hybrid energy system concept. In the example shown, a nuclear energy plant is used as the primary energy supply, supplying electricity and steam to a synfuels plant and electricity to the regional power grid that also receives a large amount of variable wind-generated power (not shown). During periods of high demand such as daylight hours or when wind generation is low, (i.e., if the wind is not blowing), the nuclear plant supplies more electricity to the grid and less steam to the synfuel plant. When demand is lower at night or if the wind farm is generating near its full capacity, the nuclear plant supplies less electricity to the grid and more steam to the synfuels plant. The natural gas plant output is modulated to maintain the steam flow to the synfuel plant consistent with its demand as the steam flow from the nuclear plant varies. This results in the high value nuclear plant and synfuels plants to operate at full capacity.

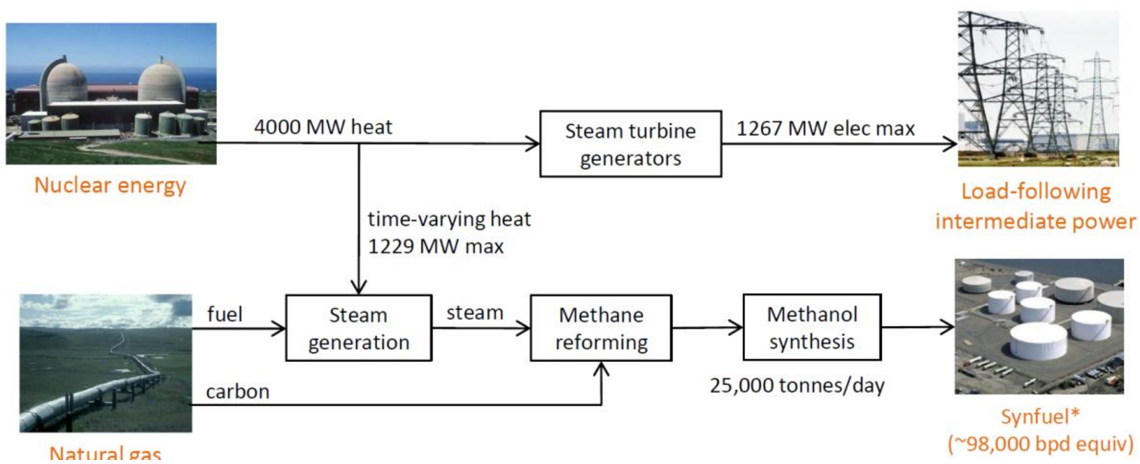

Figure 9. Integration of nuclear energy in a hybrid system with a synfuels plant to assist in smoothing variability of wind energy.

This maneuvering of the nuclear plant electricity supply to the grid and steam to the process plant supports mitigating the effects of the variability of the wind generation on the supply-demand balance of the grid while the nuclear plant continues to operate at full power. The nuclear plant provides energy to the grid and to the synfuels plant with no greenhouse gas emissions and at a long term stable price reducing the effects of the substantial variations experienced in the costs of fossil fuels, particularly natural gas, over the last few decades. The only energy supply component that varies its output is the natural gas boiler which can be designed for this purpose and operates with relatively high efficiency. This approach has an advantage over traditional maneuvering of simple cycle natural gas combustion turbines or large scale coal plants to offset the variability of wind generation by reducing emissions, (e.g., the natural gas boiler generates less CO_2 under these varying conditions than either of the traditional alternatives) and eliminates the increased maintenance burden that has been experienced by coal plants that are not designed for this type of variable operation.

The following sections discuss the application of hybrid energy systems to support mitigating the variability of high wind generation capacity on the grid and for supporting specific commodity applications off the grid.

2.1.4.3 Dynamic Operations to Smooth the Variability of Wind Energy

Figure 10 shows projected generation rates over a week for a wind farm in an area of high wind generation potential in Wyoming. As shown there are periods of high or low output that last for days, but when the generation rate changes up to full capacity variations can take place over only an hour or two. There are also periods of intermediate levels of generation. A typical grid will incorporate "spinning reserve", usually in the form of rapid-response generators typically powered by gas turbines, and other mechanisms to accommodate transients in supply and demand. The amount of such "control" generation that is normally available in a power grid to handle these other transients has been shown to be capable of also mitigating the variability of wind generation with a total capacity equal to about 25% of the system's generation capacity. A hybrid energy system able to change electricity generation rapidly enough to follow these transients would be able to combine with these other grid control systems to support the mitigation of wind generation variability. Accordingly, the incorporation of these systems into the grid could permit increasing the wind generation capacity above the 25% level.

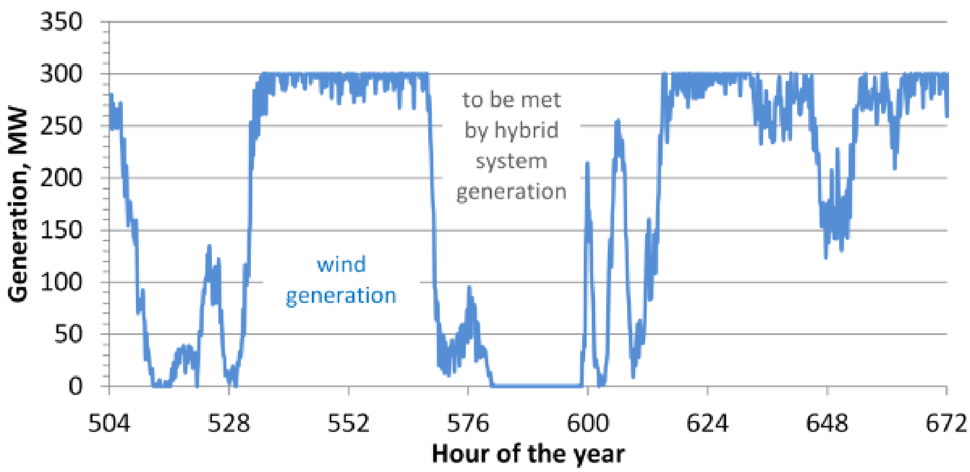

Figure 10. Projected wind generation rates for a wind farm in Wyoming

There are at least two ways to apply a hybrid energy system to smooth the variability of wind generation. In the first and conceptually simplest, the hybrid system and the wind farm are operated together to produce a combined electrical output that is constant, essentially mimicking base load generation. In Figure 10, this would correspond to supplying 300 MW at all times, or as close to this objective as possible; a fraction supplied by wind and the balance by the nuclear plant. The availability of wind generation in a region of high potential is typically 30%-45%. Accordingly, assuming a constant output is required to meet grid demand, the hybrid system would have to generate power for the balance of the operation, or 55%-70% of the time. During these periods the steam that is being sent to the process plant would be reduced to generate this additional power. To maintain the process plant operating at full capacity, as shown in Figure 9, an auxiliary fossil-fired steam generator would make up the steam flow to satisfy the needs of the process plant. Accordingly, it would have to operate at substantial power levels 55% to 70% of the time, largely diminishing the reduced CO_2 emission advantages of a nuclear-based hybrid system. Also depending on the specific location and application this may not be economic compared to just increasing the capacity of normal gird control components.

A different strategy is to address only the higher frequency components of wind's variability and let the other grid control components compensate for the rest. In this operating mode, as shown in Figure 11, by switching its energy between the power system and the process plant the hybrid energy system generates electricity so that the total of wind generation plus the hybrid system output does not change faster than a specified rate; (e.g. similar to the rate of diurnal changes). In this case depending on the specifics of the application it may be feasible to eliminate the natural gas steam plant and let the output of the synfuels plant vary as the steam flow from the nuclear plant varies. This would reduce the capacity factor and output of the process plant but would further reduce greenhouse gas emissions by eliminating the CO_2 generation from the natural gas boiler.

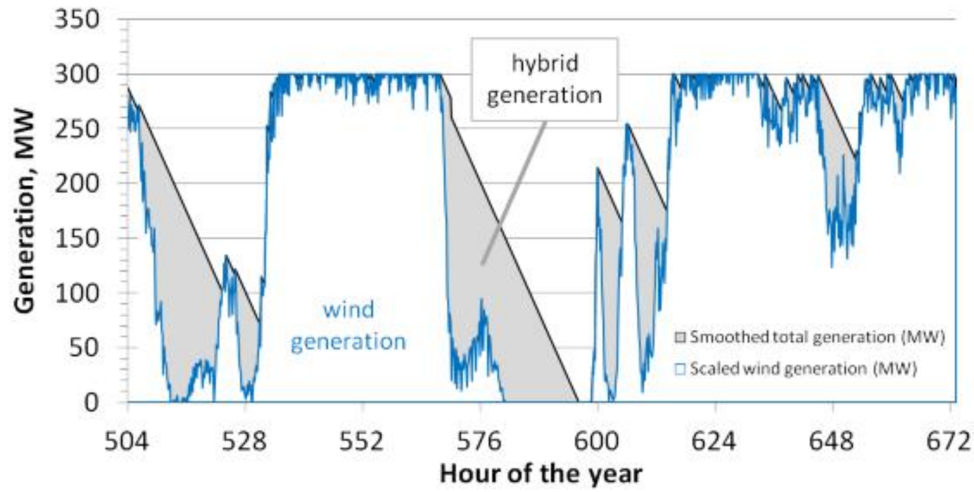

Figure 11. Application of Hybrid Generation to Smooth Variability of Wind Generation

The use of such approaches would depend on several factors such as (1) incentives to increase the capacity of wind generation on the grid above that manageable by the existing grid control equipment, (2) the technical and economic merits of adding a hybrid energy system whose economics include the production of value-added products such as synfuels, (3) the economics of incorporating a hybrid energy system for this purpose versus that of adding traditional grid control equipment, and (4) the performance and economics of the different configurations and control schemes that could be applied with incorporation of a hybrid energy system.

In any case the integration of a hybrid energy system with the grid for the purposes of mitigating the variability of wind generation will require a complex business model to meld the economics of the wind generator, the grid operator, the process plant and the energy supply(s). This involves a more complex arrangement among these entities than has been the experience in the power industry and the business practicality has not been investigated in the work completed for this technical evaluation. Accordingly, the technical and economic viability of these concepts need to be fully explored and developed in future evaluation of potential applications of hybrid energy systems.

2.1.4.4 Direct Use of Wind Energy in Support of Processes

Wind power could be used directly in a process adapted for such a variable input. One possible application is the generation of oxygen either through electrolysis or from an air separation unit (ASU). For the latter case, whether an air separation unit can be adapted to operate well at frequently varying rates is not known. In either event, a potentially viable application for this oxygen is oxy-combustion of coal or natural gas in power plants, especially if CO_2 emission limits or penalties come into effect. This process uses essentially pure oxygen to make a flue gas of concentrated CO_2 —but no nitrogen— which can be compressed and sent directly to storage sites or used for enhanced oil recovery (EOR).

Time-varying wind energy might also be used to produce clean water from currently unusable sources. Desalination to purify low quality water for potable use is another process gaining more attention in recent years. Thermal and reverse osmosis processes could be adapted to the time varying characteristic of wind generation.

In all of these processes, the ability to store the immediate product (hydrogen, oxygen, nitrogen, carbon dioxide, or water) is important to its usability in downstream processing. Storing gases at the quantities required for integration with variable power generation has been done, usually light hydrocarbons (for petrochemical feed stocks) in underground caverns solution-mined in salt domes. EOR itself is a form of gas storage, albeit with no intent to recover the gas. The availability of suitable salt domes or the usability with these gases of natural gas wells, including hydraulically fractured shale gas wells in very low permeability formations, will be a major factor in whether these processes can be used at any significant scale in Wyoming.

There has been no attempt herein to prepare a comprehensive listing of these potential applications or to develop the ones identified. The technical definition and economics of these concepts need to be developed in more detail to identify concepts that have technical and economic viability in Wyoming.

2.2 A Mix of New Generation Technologies is Needed to Replace the Aging Coal-based Generation

A notional strategy is developed that:

- Diversifies generation technologies to avoid continuing with the inelastic technology position that exists today with predominantly coal-based technology by using a mix of:
  - Wind
  - Natural Gas with carbon capture and storage (CCS)
  - Coal with CCS
  - Nuclear energy
- Reduces greenhouse gas emissions attributed to electricity generation
- Is consistent with the retirement of existing generation with age
- Provides a stable long term electricity price
- BUT, increases current electricity generation costs.

As the existing coal-fired electricity generation on the Wyoming grid ages, it will likely be replaced with a mix of technologies that will not be as dominated by coal-fired generation. This is a consequence of current, pending and potential emissions regulations that are projected to reduce the number of coal-fired plants in the United States and aging of the current fleet. These factors are projected to lead to full retirement of this current generation source over the next several decades. Also, because of these factors replacement of this generation will need to involve deployment of diverse generation technologies that reduce emissions, (e.g., toxic chemical and greenhouse gas emissions) and should provide for a stable electricity generation cost, (not significantly affected by the variability in energy costs such as has been seen in the last few decades for natural gas and oil). Figure 12 shows a notional transformation of the Wyoming electric generation sources over the next several decades that meets these objectives. The final mix of technologies includes:

- Non-emitting wind generation is increased from 16% to 23%. A limit of 25% of the total installed capacity on the grid was applied for wind generation to reduce the effect of variability in that generation on grid stability. As noted above, the use of Hybrid Energy Systems may allow increasing that limit.
- Non-emitting natural gas combined cycle generation with CCS (NGCC w/CCS) is increased from 3% to 17%. The percentage of NGCC w/CCS generation is limited to reduce the effect of possible increasing costs of natural gas on electricity costs. NGCC w/CCS plants can also be used to stabilize wind generation as part of the Hybrid Energy System configurations.

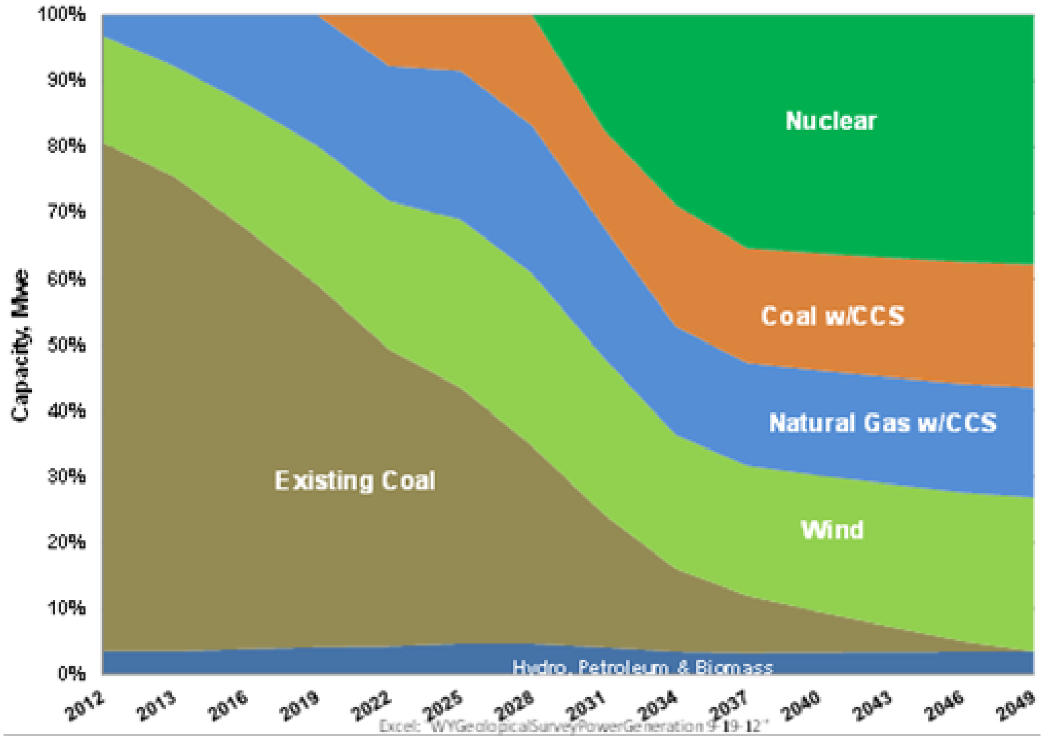

Figure 12. Notional transformation of Wyoming electricity generation sources.

- Nonemitting nuclear energy generation is increased from 0% to 38%; primarily HTGR technology deployed as part of integration with the carbon conversion industry. Small light water reactor technologies may also be included in Hybrid Energy System configurations where needed to stabilize grid operations with increased wind generation.
- Coal generation is reduced from 80% to 19%; replacing existing plants with coal-fired plants incorporating CCS[e]; maintaining a traditional market for Wyoming coal
- Hydroelectric, petroleum and biomass generation make up the 3% balance.

For the notional transformation mix, NGCC w/CCS and coal-fired with CCS are introduced in the mix for periods of retiring generation capacity prior to the availability of next generation nuclear energy technology.

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[e] There are significant uncertainties in the efficiencies, performance and costs associated with carbon capture and storage either in pure sequestration or for enhanced oil recovery. The analyses included in this transformation use projections on these technologies developed in the literature. More complete discussions of these uncertainties are included in the main body and Appendix E of *INL/EXT-12-26732, Energy Development Opportunities for Wyoming*.

The costs of electricity in Wyoming are traditionally low compared to the majority of the United States because of the large percentage of power generated using coal-fired plants. Because of this Wyoming has developed a substantial power export market; ~60% of total generation in 2010 was exported. As the coal-fired plants are retired and are replaced by newer and different generation technologies, the costs of generation will increase as shown in Figure 13 for the transformation depicted in Figure 12. Such increases are due in major part to the capital investment and are typical of installing new generation irrespective of the specific technology mix. The costs of generation for each technology are based on EIA data that projects these costs in the year 2015. This cost of generation is similar to the current costs in areas that do not have significant coal-fired generation, (e.g., the Northeast). These increases will affect the competitive position of Wyoming for export of power.

The cost of this transformation is estimated at ~$27B spread over ~40 year period. This includes the cost of nuclear power generation added to the grid during the deployment of the nuclear energy plants with the carbon conversion industry; ~$15B.

The notional transformation results in essentially no CO_2 generation when completed and could be expected to be completed only if substantive taxes or regulation of CO_2 were imposed by the government. Other less costly mixes of generation, (e.g., more nuclear energy instead of wind and coal generation) could be used in the transformation depending on the specifics of any government regulations and market trends. Regardless, any transformation that retires the current coal-fired plants will increase the costs of generation. This needs to be considered in developing the mix and deciding on the feasibility of continuing to export power. Other considerations include:

- The ability to continue to transport power out of the State over transmission lines that are already at peak capacity
- The economic trade-off of using the energy to generate electricity versus other products such as synthetic fuels and chemicals.
- The potential for increased export of wind generation to neighboring states with Renewable Portfolio Standards by displacing current coal-fired generation. Such export may not require upgrade or installation of new transmission line capacity and may be a high value market.

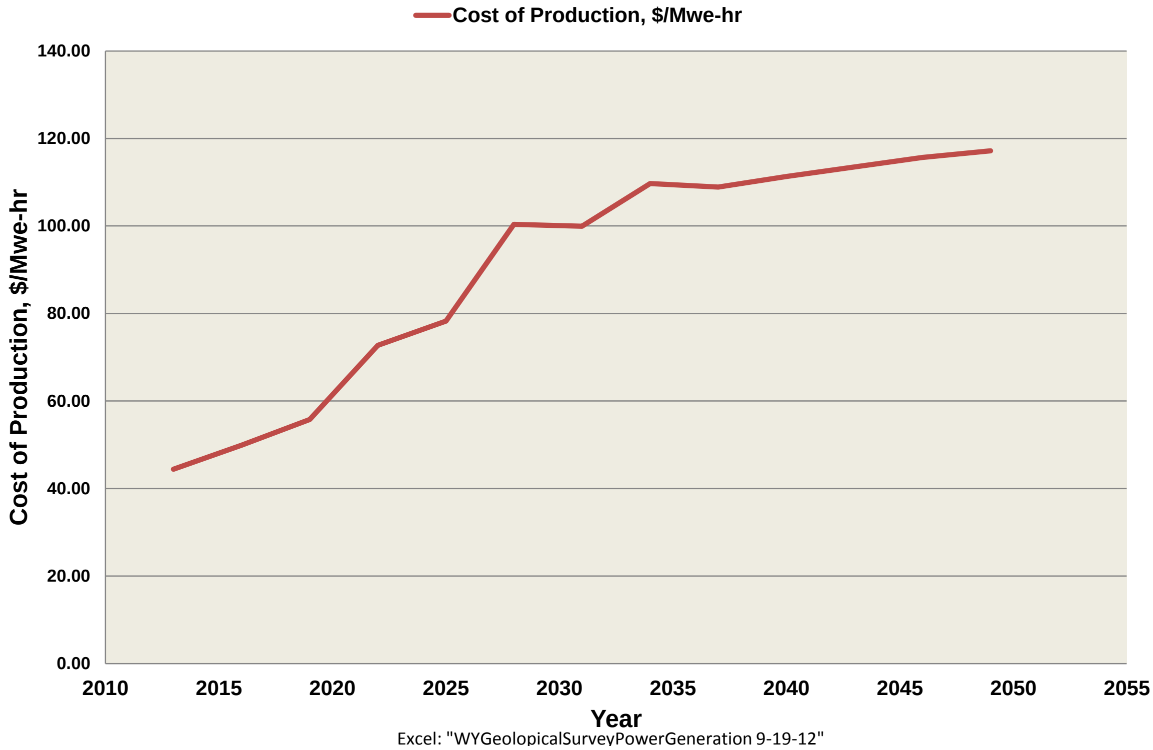

Figure 13. Cost of electric power generation for notional transformation of Wyoming electricity generation sources.

2.2.1 All Initiatives add Substantially to Wyoming's GDP

The combination of the notional deployment of the carbon conversion industry and the transformation of electricity generation sources results in substantive increases in the Wyoming GDP during their deployment and over the long term as shown in Figure 14.

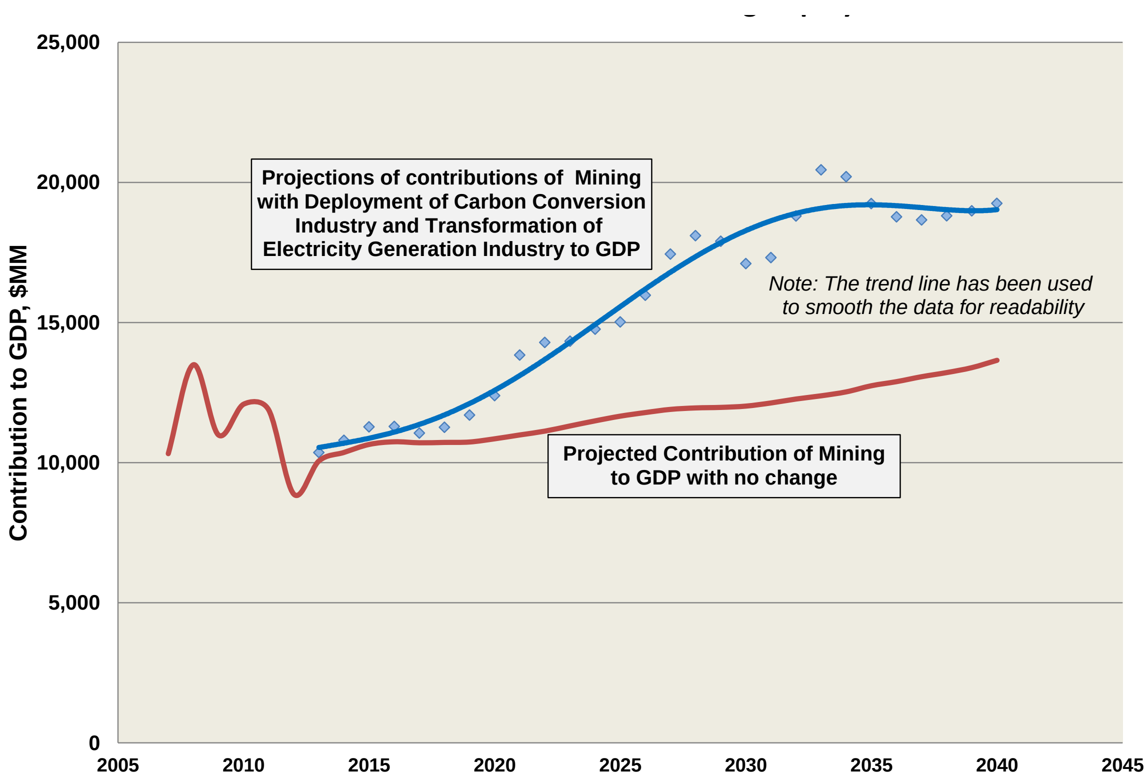

Figure 14. Contribution of carbon conversion industry and electricity generation transformation to GDP during and after deployment.

The figure shows the steady long term increase in mining GDP of ~$6B (2011$) due to the conversion of coal and natural gas to synthetic fuels and during the substitution of retiring coal fired plants with new technologies. This includes contributions of up to $14B during the construction of the carbon conversion industry and the replacement of the coal fired plants with new generation.

It should be noted that these results are for a 200,000 bpd carbon conversion industry. As long as the industry is competitive with other forms of production, increasing the size of the industry would result in correspondingly higher benefits to the State GDP.

3. MARKETS FOR INITIAL VALUE-ADDED PRODUCTS

There are three broad groups of potential products from Wyoming's energy resources: electricity, commodity chemicals, and synthetic transportation fuels. Through the operation of the carbon conversion industry, supported where necessary by hybrid energy systems, products from one, two, or all three of these could be made.

Wyoming already sends 60% of its power generation out of State over transmission lines that are generally fully subscribed. Any new generation, except if specifically intended to replace a retiring older facility, would increase the amount to be exported. Because of transmission constraints, planning to generate larger amounts of electricity may not be a preferred strategy for Wyoming. However, power generated by wind farms may be in demand by neighboring states with Renewable Portfolio Standards and limited renewable power sources. This market may not require substantial transmission development and, accordingly, could be a viable market for additional Wyoming wind generation.

Commodity chemicals present a number of possibilities as alternative markets for carbon conversion from Wyoming's coal and natural gas. Candidate products include ethylene, propylene, methanol, ammonia, and others. It is estimated that the value-added for olefins, such as ethylene and propylene, could range from a factor of 8 to 40 depending on the price for feedstock. The market penetration that can be achieved will depend on both national and international demand.

The market focused on in this report is the production of synthetic transportation fuels through conversion of Wyoming's indigenous coal and natural gas. Transportation fuels are currently made by refining petroleum. Significant production of "drop-in" synthetic fuels at prices competitive with crude oil refining and that are fully compatible with current transportation fuels could reduce the use of petroleum products thereby extending the lifetime of petroleum supplies and fuel-associated infrastructure.. Synfuel's attractive characteristics as a product include the large market for transportation fuel, the large scale at which synfuel can be produced, and its ready transport to markets outside Wyoming. Additionally, the conventional processes for conversion of Wyoming indigenous coal and natural gas to synfuels are well developed and as shown previously can be competitive with conventional crude oil refining.

As shown in Figure 15, there are medium sized refining centers near Billings, Montana; Salt Lake City, Utah; and Denver, Colorado. All of these are potential blending or distribution sites for Wyoming synfuel.

To minimize market disruption, synfuel production should not overwhelm the modest regional markets it might be sent to. One small set of options appears most attractive.

- Make gasoline as the preferred product, with diesel fuel as an alternative, because of the commercially demonstrated technology and the large markets for these products compared to other fuel or chemical choices
- Size an initial plant relatively small at about 10,000 to 15,000 barrels per day of production to reduce the overall project risk of operating a new process concept and to avoid immediately flooding the regional market with product
- Plan initially to sell the gasoline into the Colorado and/or Utah markets, or diesel fuel into all three of Utah, Wyoming, and Colorado, but allow for customers anywhere
- Transport this gasoline or diesel fuel from the initial plant by trucks and/or rail cars. The 10,000 bpd production corresponds to 30 truck shipments (full tank trailer with a second "pup" trailer behind) per day, or 17 railroad tank cars per day, both modest amounts of traffic.

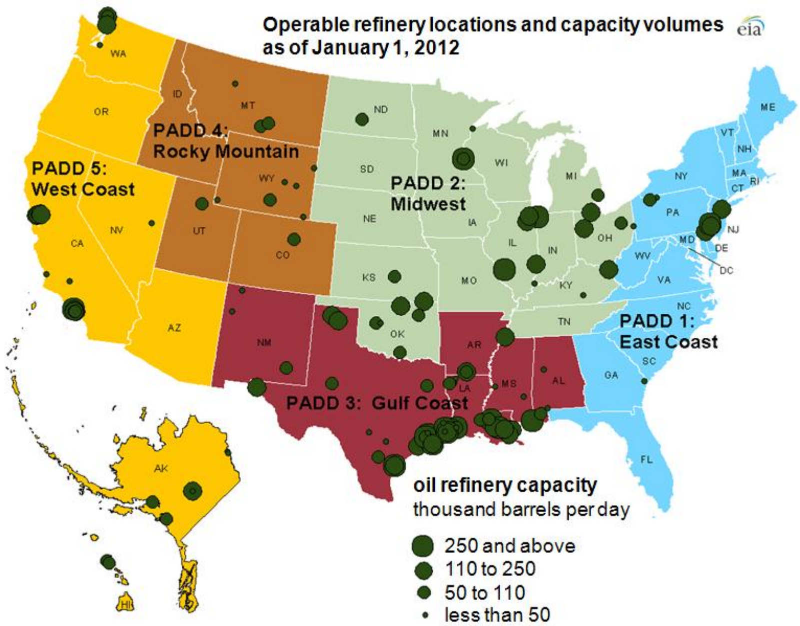

Figure 15. Refinery locations (Source: EIA, 2012).

- Depending on market forces, distribution centers, experience with the initial plant, expand this plant to full capacity, expand distribution to centers that provide access to wider national and international markets and continue to deploy a larger carbon conversion industry.

3.1 Infrastructure Development

There are multiple needs and opportunities for infrastructure expansion and development to support deployment of a carbon conversion industry incorporating nuclear energy technology and transforming the electric power industry in the State

- Industrial equipment manufacturing capabilities ranging from large pressure vessel material forging and fabrication to digital electronics
- Transportation and distribution capabilities for the feedstock and products produced in the carbon conversion industry
- Education and training capabilities to develop and maintain a technically competent workforce

The extent to which these capabilities are, or become, indigenous to Wyoming is directly a function of the character, size and pace at which a carbon conversion industry is developed and the electric power industry is transformed.

Whether these infrastructure capabilities are indigenous will depend to a great extent on the incentives offered industry to invest in industrial facilities and the education system in Wyoming. No attempt is made to quantify the effect of such infrastructure expansion and development on the economy of Wyoming. However, to provide some perspective, if the industrial equipment manufacturing capability needed to accomplish the notional scope of a carbon conversion industry and transform the electric power industry were located in Wyoming, there would be a greater than a 30% increase in the contribution to the GDP compared to that shown in Figure 14.

Each of the affected areas is addressed in the following subsections.

3.1.1 Industrial Equipment Manufacturing

Direct construction costs for the notional carbon conversion industry and transformation of the electric power industry breakdown as follows:

- Equipment (28%)
- Material (38%)
- Labor (28%)
- Engineering (8%).

The extent to which this manufacturing is performed by companies already within Wyoming or from industries developed within Wyoming will determine the contribution to the State and local areas revenue and the State's GDP.

The economic results discussed in early sections of this report have assumed that all of the equipment and some of the engineering would not be from within Wyoming. Accordingly, there is the potential to increase the revenue to Wyoming during construction by up to 30% by bringing this manufacturing capability into the Wyoming scope of supply.

3.1.1.1 Equipment

The major equipment required in the process plants and HTGR plant includes:

Process Plant Vessels

In general, the largest pieces of equipment in a synthetic fuels plant are the reactors, gasifiers and related equipment. The following are approximate characteristics of these vessels:

- Fischer-Tropsch Reactor—10 meters in diameter by 60 meters tall; ~ 2,100 tons
- Gasifier—5 to 6 meters in diameter; height of 50 meters
- Syngas cooler—4 meters in diameter and a height of 64 meters
- Methanol synthesis reactors—6 meter inside diameter.

Process Plant Pumps, Valves, and Piping

Piping and valves account for a significant fraction of the cost of a synthetic fuels or chemical plant. Typically these costs can range from 18 to 61% of the FOB equipment cost, which would normally represent about 7 to 15% of the installed plant cost. Therefore, the cost associated with piping and valves for such a plant are obviously significant.

HTGR Major Components

Seventy-five percent of the equipment cost of a HTGR plant is made up of the following components and systems in the order of their relative costs:

- Reactor building
- Reactor vessel
- Reactor initial core
- Reactor metallic internals
- Reactor graphite internals

- Reactor cavity cooling system
- Core refueling equipment
- Heat rejection system
- Heat transport system
- Power conversion system.

The primary system vessels which include the reactor vessel, the crossover vessel and the heat transport system vessel are among the more costly items in the plant. They are also heavy and large and not transportable by rail or road, so unless the plant is located on a major waterway the vessels will be fabricated on or near the plant site. The development of the remote fabrication facility and its operation during construction of the plant is a significant opportunity for a local qualified vessel manufacturer.

Each of the systems is comprised of many valves, blowers (circulators) and pumps that represent a significant fraction of their costs similar to that cited for the process plants.

Additionally, depending on the extent of commitment to nuclear energy, the infrastructure for fabrication of nuclear fuel is an important part of supporting the operation of these plants with expected 80 to 100 year lifetimes. Nuclear energy plant refueling occurs at one year to 18 month intervals.

3.1.1.2 Materials

Significant quantities of concrete and steel (structural and siding) are used in the construction of all of these plants. Typically concrete plants are constructed at the site to support construction. This would be an indigenous contribution to the State revenue.

Steel will likely need to be procured from multiple sources within and without Wyoming. The large scale and wide spread construction attendant to the initiatives discussed herein would provide a basis for development of a steel distribution company within Wyoming.

Other building material suppliers should be indigenous to Wyoming.

3.1.1.3 Crafts and Engineering—Education and Training

A well-educated and trained, technically competent work force is essential to the successful development of a carbon conversion industry and transformation of the electric power industry to include diverse generating sources. In brief:

- Designing, licensing/permitting and maintaining these industries will require university educated engineering and scientific personnel at both the bachelors and graduate levels
- Construction will require crafts personnel trained and experienced in trades such as welding, pipe fitting, electrical and computer systems
- Plant operations and maintenance will require technician-level training in the respective technologies (e.g., chemical processes; nuclear energy systems; computer systems).

The companies that will invest in, develop and build the process plants and power generation plants could be expected to initially import the management and senior technology personnel. However, typical experience is that the bulk of the industrial workforce for construction, operations and maintenance will need to be developed from within the indigenous population.

3.1.2 Transport and Distribution Systems

As the carbon conversion industry is developed, it is important to evaluate the most important markets and the means of transporting the feedstock (coal and natural gas) and transporting and distributing the products, whether by waterways, truck, rail or pipeline. Further, if a distributed configuration for a carbon conversion industry should evolve, a system of pipelines will be required that interconnect the process plants producing synthesis gas and the various process plants that produce synthetic fuels and chemicals.

At the outset, a notional initial coal and natural gas conversion plant could utilize existing rail and truck transport infrastructure. As the carbon conversion industry expands, existing infrastructure is anticipated to be inadequate and planning for production, transport and distribution needs to be accomplished in an integrated manner, with necessary participation by the investing industries and consideration of necessary incentives for investment in an anticipatory manner.

Further, as the electric power generating industry is transformed, the electric transmission system will need modification and enhancement depending on the specific types and location of the new generating plants, and the extent of electric power export that is planned.

3.1.3 Value-Added Processing of Uranium

There are potential opportunities to produce value-added downstream products from uranium mined in Wyoming. Of the several steps between yellowcake and installed nuclear fuel assemblies, only the conversion of yellowcake U_3O_8 to uranium hexafluoride UF_6 appears to have need for new capacity. There are only two such conversion plants in North America, both 50-60 years old. A plant running this process would use skills that should already be present in Wyoming's other mineral processing industries. This specialized opportunity to process uranium for users throughout North America merits further examination.