Chapter 12
The Carbon Management Institute's Integrated CO_2 Storage/EOR Strategy: the Advantages of Deploying Innovative, Multiple-Resource Development Strategies Designed to Foster Sustainability of Energy and Environmental Resources

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Abstract The Powder River Basin (PRB) offers an opportunity to illustrate the advantages to Wyoming of deploying an innovative, multiple-resource development strategy designed to foster the sustainability of the state's energy and environmental resources. Such a multiple resource development plan is based on viewing the PRB's particular assemblage of energy/environmental resources as a synergistic system rather than a collection of disparate parts. This approach relies on synergistic relationships among resource elements in order to increase the efficiency of development, minimize environmental degradation, sustain long-term resource use, and maximize revenue to the state.

The key resource elements of an integrated development strategy for the PRB are:

- Coal resources and mines (vast coal reserves)
- A significant source of water (groundwater produced during coalbed methane development)
- Coal-to-chemicals plants capable of capturing CO_2 (located at mine-mouth sites)
- Nearby CO_2 storage sites (depleted, Cretaceous compartmentalized gas fields)
- Depleted oil fields suitable for enhanced oil recovery (significant amounts of stranded oil)
- CO_2 storage in these depleted oil fields (doubling the geologic CO_2 storage capacity)

By developing this suite of resource elements as a system, it would be possible to optimize the benefits to the energy industry while maximizing the sustainability of

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energy resource development, and maximizing state revenues for future generations. In addition, the strategy described here would reverse the regional trend of coal- and energy-related job loss. Most importantly, all of this resource development can be accomplished within the existing regulatory framework and without significantly increasing the industrial footprint. It is vital to our future that Wyoming seek new, more effective, efficient, and sustainable approaches to energy development.

12.1 Introduction

The resource-rich Powder River Basin (PRB) of northeastern Wyoming offers an ideal opportunity to design and implement a new and different approach to future energy development in the state. This chapter explores formulation of an integrated energy development platform for the PRB that emphasizes synergistic relationships in order to optimize the effective and efficient exploitation of the state's energy resources while minimizing environmental damage. The basic tenet underlying this approach is that it is more effective and efficient to develop a set of resources together/concurrently rather than separately.

12.2 Resource Elements

We first identify the resource elements associated with the area of interest. The key resource elements that illustrate the power of an integrated developmental strategy for the Powder River Basin are:

- Coal resources and mines (with large reserves)
- Significant source of water (groundwater produced during coal bed methane development)
- Coal-to-chemical plants capable of capturing CO_2 (mine-mouth location)
- Nearby CO_2 storage sites (depleted, compartmentalized gas fields)
- Depleted oil fields suitable for enhanced oil recovery (significant amounts of stranded oil)
- Additional CO_2 storage in depleted oil fields

Using these six key resource elements, it is possible to neatly explain and illustrate the effectiveness of this new approach to energy resource development in Wyoming, and how this approach can be used to minimize environmental degradation.

12.2.1 Coal Resources

Wyoming has 65 billion tons (65 Bt) of coal reserves – 46 billion tons (42 Bt) of which are recoverable using current mining technology – and additional vast coal resources that will become reserves with the advent of new mining techniques. At

Fig. 12.1 Active coal mine in Wyoming's Powder River Basin. Wyoming's coal industry contributes US $ 1.2 billion annually to state revenues. (Meg Ewald photo)

current rates of extraction, the state's coal reserves will last well into the next century. Most importantly, the PRB has a huge coal asset (the basin produces 40 % of the nation's coal) that is currently exported via rail (approximately 450 million tons (410 Mt per year) to support coal-fired power generation at 135 facilities in 39 states, including Wyoming (Jones et al. 2009) (Fig. 12.1). Presently, Wyoming coal (Table 12.1) supplies the nation with approximately 8 quadrillion Btus of energy per year, or 8 % of the total annual U.S. energy budget (Surdam 2008). Additionally, on a cost-per-Btu basis, Wyoming coal is the nation's cheapest large-scale source of energy (Fig. 12.2). Moreover, Wyoming coal has remained an extraordinarily reliable energy source with dependable long-term delivery schedules and an absence of unpredictable price spikes.

A paradox facing Wyoming's coal industry is a very uncertain future in supplying the nation's dwindling fleet of coal-fired power plants, but a very bright future with respect to a new coal-to-chemicals industry (Fig. 12.3). The technology to support such a value-added industry is available, but has not yet been deployed in the US. In contrast, China currently uses coal as feedstock to produce commercial quantities of methanol, ethanol, acetate, olefins, ammonia, diesel, and gasoline, among other products. Inherent in these coal-to-chemical technologies is the ability to capture CO_2. Therefore, the critical question for these types of industrial facilities is this: *Can the captured CO_2 be stored successfully in geologic storage sites?*

In a future carbon-constrained world, the EPA will regulate CO_2 and other greenhouse gas (GHG) emissions in the U.S. under the Clean Air Act (Massachusetts v. EPA Supreme Court ruling, 2007). The EPA has declared that GHGs pose a danger

Table 12.1 Top ten exporters of energy to the United Sates in 2006

		Crude Oil		Natural Gas		Coal		
Rank	Country or state	MM bbls/yr	Quadrillion Btus	Tcf	Quadrillion Btus	MT/yr	Quadrillion Btus	Total (Quadrillion Btus)
1	Wyoming	52.93	0.28	1.75	1.77	446.74	7.96	10.01
2	Canada	648.97	3.41	3.59	3.63	1.49	0.04	7.08
3	West Virginia	1.83	0.01	0.22	0.22	152.37	3.91	4.14
4	Mexico	575.61	3.02	0.01	0.01	0	0	3.04
5	Saudi Arabia	519.40	2.73	0	0	0	0	2.73
6	Venezuela	416.83	2.19	0	0	3.07	0.08	2.27
7	Nigeria	378.51	1.99	0.06	0.06	0	0	2.05
8	Alaska	270.47	1.42	0.42	0.43	0	0	1.85
9	Iraq	201.85	1.06	0	0	0	0	1.06
10	Angola	187.25	0.98	0	0	0	0	0.98
	Total	*3,253.61*	*17.08*	*6.05*	*6.12*	*603.67*	*11.99*	*35.19*

Note: total may not equal sum of components because of independent rounding. Coal imports include coal to Puerto Rico and the U.S. Virgin Islands.
Sources: Bureau of the Census, U.S. Department of Commerce, Monthly Report IM 145
EIA, U.S. Natural Gas Imports by Country
EIA, U.S. Crude Oil Net Imports by Country
EIA, Gross Heat Content of Coal Production, Most Recent Annual Estimates, 1980–2006

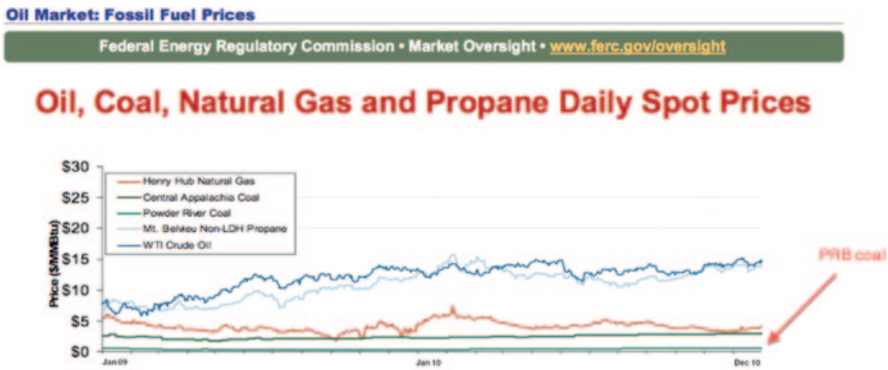


Fig. 12.2 Two-year price trends contrasting Powder River Basin coal with other energy sources. Note low price and lack of price spikes with respect to PRB coal

to public health and welfare, and the agency will regulate them as pollutants under the act. Indeed, the agency began to do so early in 2012 when it released new emissions standards for new construction or modification of coal- and natural-gas-fired power plants. As a result, carbon capture and storage must succeed if any new or modified coal-based industrial facilities are to be constructed in Wyoming, or elsewhere in the nation. In any discussion of energy issues, particularly with respect to Wyoming, it is important to remember that coal is our nation's most abundant, readily available, and cheapest form of energy ($ 0.50 per million Btus, vs. natural

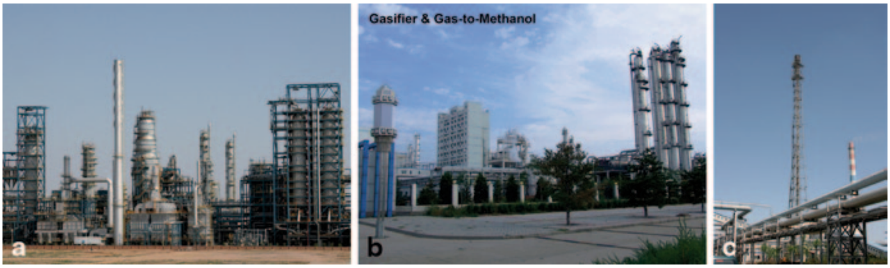


Fig. 12.3 (**a**) Coal-to-diesel plant and (**b**) coal-to-methanol plant, Shaanxi and Inner Mongolia provinces, China. By 2015, China will produce 280 million barrels of methanol, 14 million barrels of diesel, 100 million barrels of acetate, and 1.2 trillion cubic feet of syngas from coal ($ 34 billion worth of products) annually. Coal conversion technology already exists and has been proven on a commercial scale, and Wyoming has all of the resource elements necessary for successful development of a coal conversion industry in the state. (**c**) Coal-to-methanol facility in Shaanxi Province. The tall structure in the center of the photo is the CO_2 emission stack. Conveyor belts used to transport coal from the mine to the facility can be seen at the bottom right and bottom left edges of the photo. (John Jiao photos)

gas at about $ 3 per million Btus). Without proven, effective carbon storage, any future regulation of carbon emissions will jeopardize access to and use of Wyoming's huge coal resource. An example of the intense pressure facing the nation's aging coal-fired power generating fleet is the April 14, 2011 announcement of a legal settlement over air quality concerns that led the Tennessee Valley Authority to agree to close 18 coal-fired units at three facilities (i.e., 16 % of TVA's power generating capacity) over the following five years. This agreement includes substantial fines, $ 350 million for environmental projects, a loss of 2700 MW of power and 300 TVA to 400 TVA jobs, and a decreased demand for Wyoming coal on the order of 1 million tons (0.9 Mt) per year.

In this chapter, the Carbon Management Institute outlines a strategy that prevents the damage to Wyoming's economy that would result from any significant bypassing of Wyoming's coal resources. Enhancing the value of PRB coal by encouraging the growth of value-added coal products that can be produced with minimal environmental damage is a key element in any future PRB energy development scenario.

12.2.2 Water

The most readily available water resource in the PRB is the groundwater produced by the coal bed methane (CBM) industry. Production experience gives a typical fluid/gas production scenario for a CBM well as follows (Fig. 12.4a):

- The well produces substantial amounts of water in the first year or two of operation as hydrostatic pressure decreases.
- Gas production peaks at the end of year one or during year two.
- Production of water/gas declines steeply over the next three to five years.
- The productive life of a typical CBM well is usually five to ten years.

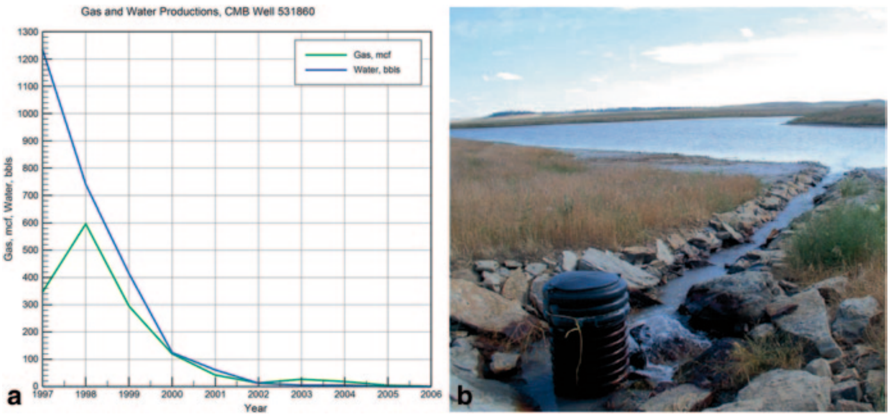


Fig. 12.4 (**a**) Annual gas and water production curves of CBM well Thielen 20-41. Note that this typical well produces substantial amounts of water in the first two years, and that gas production peaks in the second year. (Reprinted from Surdam et al. 2007). (**b**) Groundwater produced during coal bed methane development flows into a containment pond in Wyoming's Powder River Basin: this is a typical water discharge scenario in the basin. (John Jiao photo)

This scenario represents the typical production behavior of an average CBM well in the PRB, but this average encompasses a wide range of production values (some CBM wells have produced only gas, and others have yielded only water over a five-year period).

Water production has proved the most controversial aspect of CBM development in the PRB. The problem stems from the fact that the CBM produced water in the basin is typically sodic, with sodium adsorption ratios (SAR) of 2–6 milliequivalents per liter or more. The water has salinity values of 500 mg/L–3500 mg/L, but in a region with sodic soils (such as the PRB), the water's high sodic content renders it unsuitable for agricultural use without treatment. Therefore, beneficial use of CBM produced water is problematic. Excluding Anadarko's use of CBM water in its water-flooding operation at the Salt Creek oil field and a small amount of treated water, the produced water is not put to beneficial use once it reaches the surface, but is instead discharged into nearby streams and ponds (Fig. 12.4b). Consequently, a very contentious atmosphere has emerged concerning what some perceive as "wasted" CBM produced water, particularly with respect to handling and disposal. The recent non-degradation ruling regarding waters entering Montana from Wyoming will exacerbate the combative discussions of CBM produced water issues. The relevant question for our purposes is this: *How large is the water resource associated with CBM activity in the PRB, and how long will it be available?*

To answer these questions, the Wyoming State Geologic Survey (WSGS) studied CBM production records extensively, using the Wyoming Oil and Gas Conservation Commission (WOGCC) database to evaluate gas and water production histories of 22,211 CBM wells over nearly a decade (1997–2006; see Surdam et al. 2007). Using the results of this study and estimating the number of CBM wells slated for development in the PRB, the WSGS predicted CBM water production over the next decade (through 2020). Estimates of future drilling activity for CBM production in the PRB were based on approved and pending environmental documents, BLM permitting activity, WOGCC records, and estimates from the Wyoming Department of Environmental Quality and the Wyoming State Engineer's Office (Surdam et al. 2007; Fig. 12.5a).

In summary, the water/gas production histories of 22,211 CBM wells two years old or older in the PRB (as of 2007) showed that these wells typically produced approximately 2.3 trillion cubic feet (TCF) of gas, and approximately 4.2 billion barrels of water (1 barrel = 42 gallons; Surdam et al., 2007). The average water/gas ratio for the wells studied is 1.83 barrels of water per thousand cubic feet (MCF) of produced gas. Although it is difficult to predict future production trends based on CBM well production histories in the PRB, if it is assumed that CBM wells have a five-year lifespan and the estimated number of CBM wells that will be drilled over the next decade are used in the analysis, calculations suggest that on average, CBM activities in the PRB will produce one billion barrels of water annually. (These estimates of produced and available CBM water exclude the water currently used by Anadarko in its Salt Creek enhanced oil recovery project.) For the next 10–20 years, approximately one billion barrels of CBM produced water will be available annually in the PRB for beneficial use in industrial endeavors.

If a coal-to-chemical industry requires additional water resources, deep basin brines could meet this demand. At depths greater than 10,000 ft present-day depth in the center of the PRB, the Paleozoic Madison and Tensleep formations contain fluids with salinities (TDS) greater than 10,000 ppm (Fig. 12.5b). Therefore, the deep Tensleep and Madison formations do not contain drinking water as defined by the Safe Drinking Water Act (TDS < 10,000 ppm). Consequently, the Madison/Tensleep fluids could either be used at in-situ composition, or could be produced and treated to a composition compatible with industrial processes. Aines et al. (2010) showed that, using an osmotic pressure limit of 1200 psi, a Tensleep brine (Na-Cl-SO_4; TDS of 25,000 ppm) can be treated via reverse osmosis (RO) at 50 °C to achieve up to 80 % water removal. In conventional desalination applications (i.e., treatment of seawater), much of the cost of the procedure stems from the energy required to pressurize the treatment system. However, in treating the produced brine, pressure is an asset rather than a problem because the fluid arrives already pressurized (in-situ formation fluids in the Madison/Tensleep formations in the PRB at 10,000 feet present-day depth have pressures of 4500 + psi). As a result, treating produced fluids, excluding the drilling and production expense, costs half as much as treating seawater with RO (Aines et al., 2010). Reverse osmosis yields a product (fresher water) that would meet industrial specifications, and any residual brine could subsequently be re-injected into the deep formations. The first choice of water for a coal-to-chemical industry remains CBM produced water, but treated deep formation fluids would serve as an alternate source if additional water is required. Importantly, the deep formation fluids could be produced with no effect on shallower subsurface potable water resources. The use of deep formation fluids would not compete with domestic or agricultural interests, nor would it degrade surface or subsurface water resources.

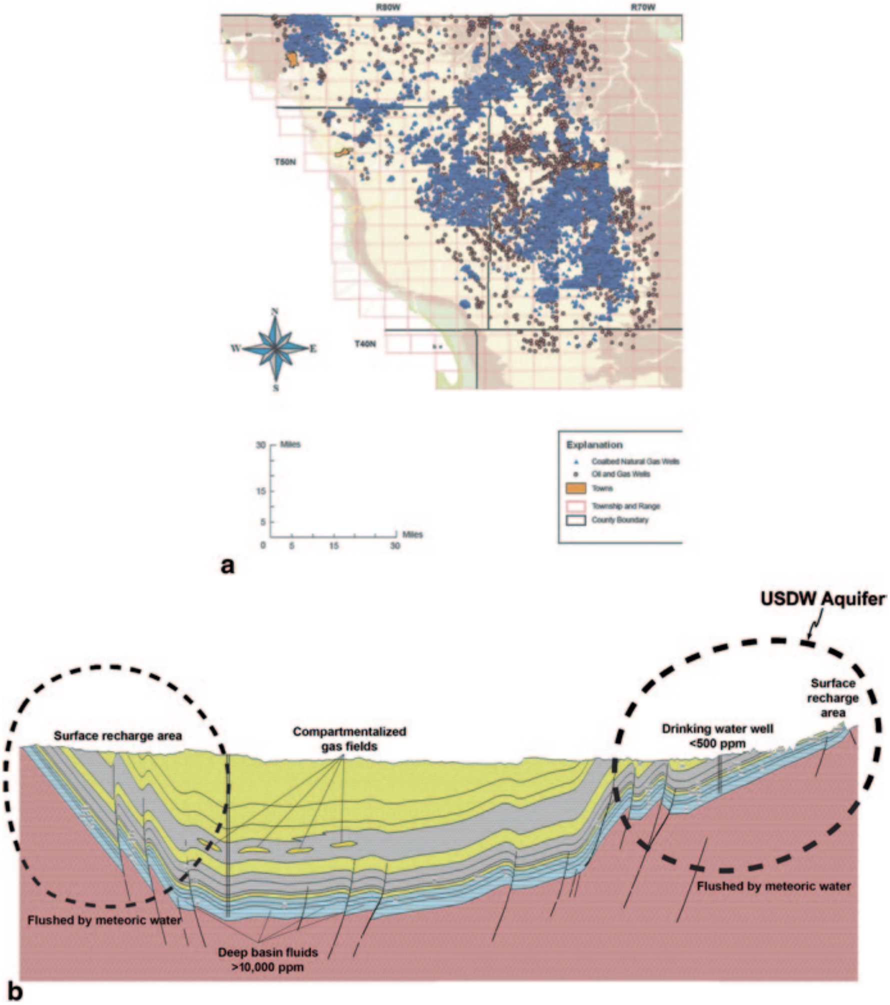


Fig. 12.5 (**a**) Map showing the distribution of coal bed methane wells – along with oil and conventional natural gas wells – in Wyoming's Powder River Basin. (Reprinted from Copeland and Ewald 2008) (**b**) Cross section showing aquifers and water recharge zones in relation to depleted gas fields and deep basin brines in Wyoming's Powder River Basin

12.2.3 Coal-to-Chemical Applications

Though coal-to-chemical technology has not yet been deployed in the U.S., China has developed and used this technology to spawn a huge chemical industry. At present, China generates commercial quantities of methanol, ethanol, olefins, ammonia, acetate, diesel, and gasoline, among other chemicals. For example, in Shaanxi Province, six coal-to-methanol plants each produce 0.5–0.7 Mt of methanol annually.

Over the next five years, the province plans to double the current number of coal-to-methanol plants; when that occurs, Shaanxi Province will produce almost all the methanol required by the Chinese fabric industry. As an aside: synthetic fibers and blends of natural and synthetic fibers produced in China are derived from coal. So, if you are wearing garments made in China, you are most likely wearing Chinese coal.

The following aspects of the coal-to-methanol plants in Shaanxi Province are pertinent:

- Plants are located at coal mine mouths (Fig. 12.3c).
- The methanol plants use coal gasifiers (Fig. 12.3b; the building in the center of the photo houses a GE gasifier).
- The CO_2 emitted by these plants is captured (95+% pure CO_2) and vented (Fig. 12.3c). In the near future, the CO_2 captured at these plants will be used in tertiary recovery projects in nearby depleted oil fields or stored for future use.
- A typical coal-to-methanol plant uses 1.8 Mt to 2.0 Mt of coal annually, emits 4 Mt of CO_2, and uses approximately 6 Mt of water.

Also relevant to the present discussion is the emergence of a coal-to-diesel industry in China. Annually, each coal-to-diesel plant produces 7–14 million barrels of diesel, uses 3.5 Mt to 7 Mt of coal, captures 2 Mt to 4 Mt of CO_2, has an 8:1 water to diesel ratio, is 60% efficient (using sub-bituminous coal), and requires a crude oil price of $ 50/barrel to break even. The coal-to-diesel plant shown in Fig. 12.3a uses a hydrolysis/catalysis process developed in China. It is a mine-mouth industrial plant capable of producing commercial quantities of a coal-derived, value-added product: diesel fuel. A variety of coal-to-chemical technologies are being employed profitably overseas, especially in China, and the deployment of these technologies in the U.S. is only a matter of time. The coal-to-chemical technologies embraced by China have two great advantages: all the production plants have the inherent ability to capture CO_2, and all the plants generate products that substantially increase the value of coal (see Fig. 12.6 for an example illustrating this point).

Although a robust coal-to-chemical/syngas industry has not developed in Wyoming, it is simply a matter of having the creative will to try something new that provides the resource sustainability inherent in that industry. Thankfully for future generations in Wyoming, economics will eventually force the issue and accelerate the transition to a better, more responsible use of the state's coal resources. To illustrate this point, consider Fig. 12.6, which shows the value-added potential of Btu conversion technologies to coal reserves (Childress 2011): if sold as coal (coal is mined and transported to customers via rail), Peabody Energy's coal reserves are worth US $ 288 billion, but if sold as motor fuel (coal is gasified and converted to gasoline/diesel), the same reserves are worth US $ 3.6 trillion. Using gasification, the coal-to-liquids/syngas technologies inherently capture and provide storage-ready CO_2, and most importantly, increase the value of the resource by an order of magnitude.

In summary, the Wyoming PRB has all the resources, including human resources, necessary to support the deployment of a robust industry based on converting

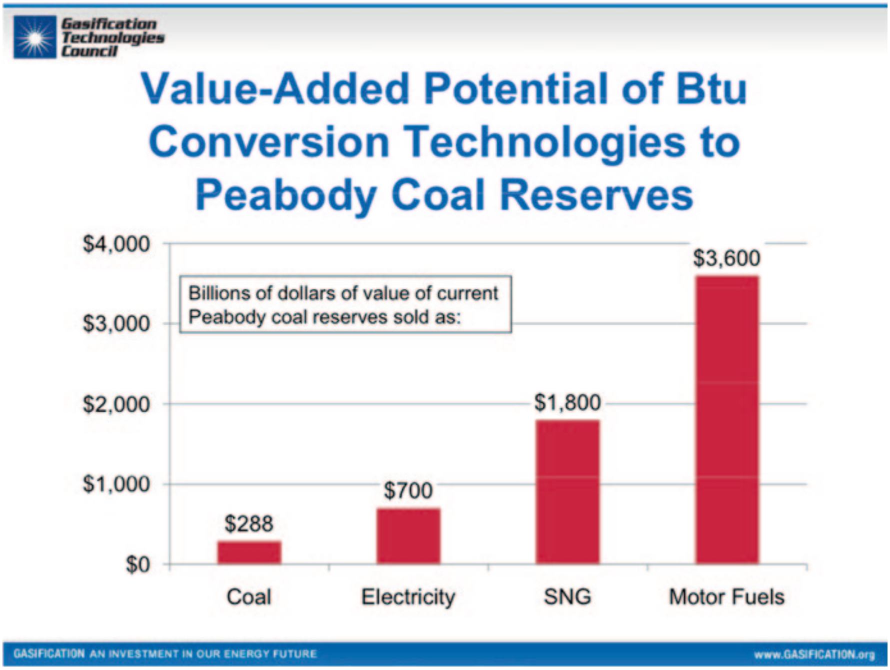


Fig. 12.6 Value of Peabody Energy Co.'s coal reserves sold in different forms. Technologies that inherently capture CO_2 (coal converted via gasification to gas/liquid fuels) add significant value and provide storage-ready CO_2. (From Childress 2011)

coal to added-value products. Development of such an industry in Wyoming could be accomplished in a decade or less. In Shaanxi Province, China, six plants were constructed in five years, and an additional six or more facilities are slated for construction over the next five years. The technology has existed since before World War II, and is presently being modified, improved, and deployed in China on a huge scale.

12.2.4 CO_2 Storage

In other Laramide basins in Wyoming, the Pennsylvanian Tensleep/Weber sandstones and Mississippian limestones are potential targets for CO_2 storage. For example, in the Greater Green River Basin, the Weber Sandstone and Madison Limestone have great potential as CO_2 storage reservoirs, especially on the Rock Springs Uplift and Moxa Arch (Surdam and Jiao 2007; Surdam et al. 2009). At both sites, the Weber and Madison formation fluids consist of brines (salinity > 70,000 ppm). In the Greater Green River Basin, these two Paleozoic units – because of a relatively recent basin inversion and a lack of meteoric water recharge – produce saline waters; in the PRB, however, these units produce copious quantities of potable water at relatively shallow depth (< 5000 ft), particularly at the eastern basin margin owing to meteoric water recharge and fresh water flushing (Fig. 12.5b). Regulations being promulgated by the U.S. Environmental Protection Agency will prohibit CO_2 injection (Class VI wells) into Underground Source of Drinking Water (USDW) aquifers; as a result, CO_2 storage in the Pennsylvanian/Mississippian stratigraphic section in the Greater Green River Basin will be possible, but storage in these units in the PRB will prove more problematic. Therefore, alternate CO_2 storage reservoirs must be identified in the PRB.

The prime candidates are depleted and originally abnormally pressured gas fields. In the PRB, the Cretaceous stratigraphic section is dominated by relatively low-permeability lithologies (shales and siltstones), and contains relatively thin, discontinuous valley-fill and shore-face sandstones (Muddy Sandstone), offshore marine bars (Shannon Sandstone), and beach sandstones (Frontier Formation). Where this collection of Cretaceous shales and sandstones ocuur at a present-day depth of 8000 ft or more, the section is typically overpressured (Fig. 12.7a) (Surdam et al. 2005). The various discontinuous sandstones within the overpressured shales are gas-charged: most of these Cretaceous anomalously pressured sandstones have produced gas since the 1960s and presently host highly depleted gas fields (Fig. 12.7b, c, d). Typically, the shales are gas-charged and anomalously pressured from approximately 8000 ft present-day depth down to the lowest organic carbon-rich shale in the Cretaceous stratigraphic section (Surdam et al. 2005). The top, bottom, and lateral extent of the anomalously pressured section can be mapped successfully by examining the sonic and seismic interval velocity distributions for specific lithologies (Fig. 12.7a); the velocity of a specific lithology slows substantially within the low-permeability volume when it is gas-charged and anomalously pressured. Above the anomalously pressured section, many of the marine sandstones have been flushed with meteoric water, but within the anomalously pressured volume, the sandstones contain fluids similar in composition to fluids in the rocks as originally deposited (sea water) (Fig. 12.8). This suggests that the sandstones within the anomalously pressured volume have been and remain isolated from meteoric water recharge (potable water). Thus, CO_2 stored in depleted gas fields within the anomalously pressured Cretaceous rock volume would have no interaction with or deleterious effects on potable water in the PRB.

Each of the significant Cretaceous depleted gas fields in the PRB were evaluated for CO_2 storage potential (Table 12.2). The screening process began with a compilation of production histories of all oil and gas fields in the PRB, for it was assumed that depleted fields with the highest cumulative production would have the greatest storage capacity. All oil and gas fields in the basin were listed according to cumulative production, from highest production to lowest. Next, the list of potential fields was reduced to include only Cretaceous compartmentalized fields: criteria for this decision included type of reservoir drive mechanism, reservoir depth, producing formation, and initial reservoir pressure. Lack of a water drive and initial overpressuring were preferred because data indicated that after depletion, pore space would be available in the reservoir and would not have been refilled with formation fluid after the removal of hydrocarbons. Anomalous pressure (overpressure) indicates a closed rock/fluid system (compartmentalization) isolated from meteoric water recharge.

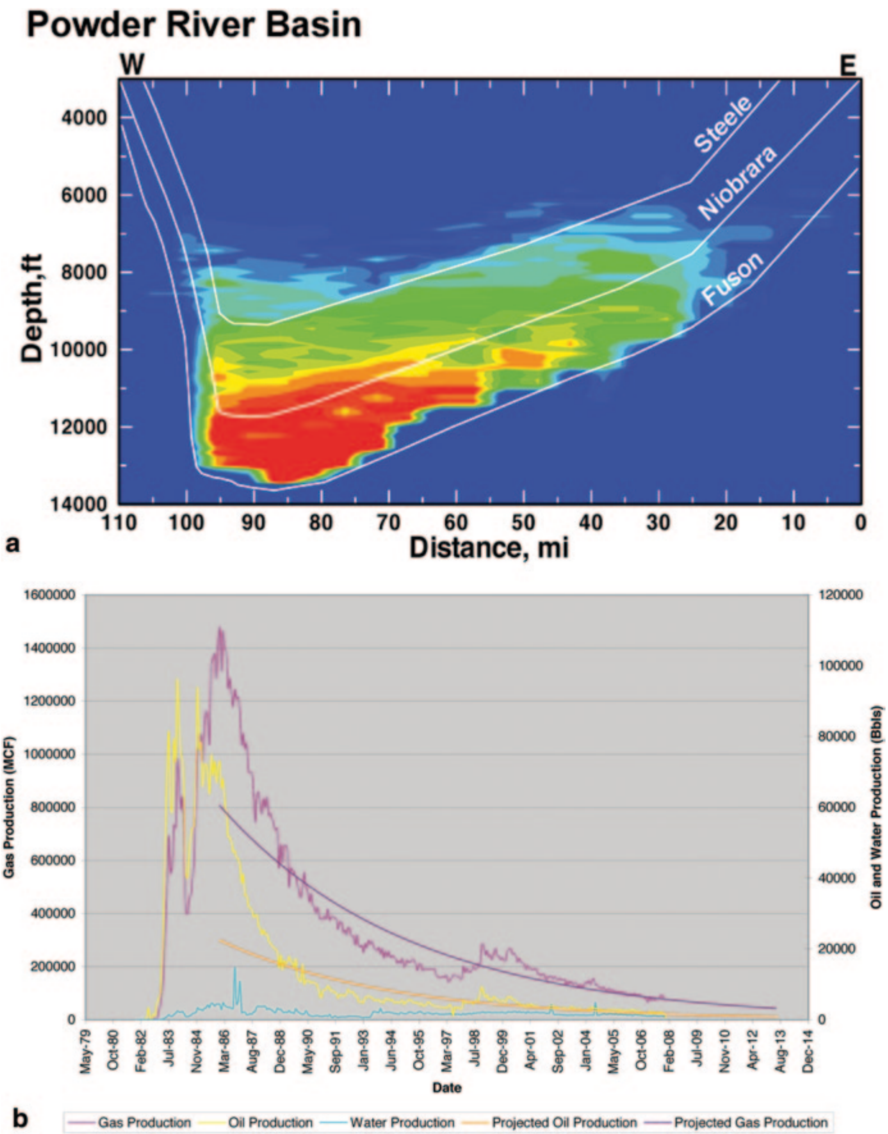
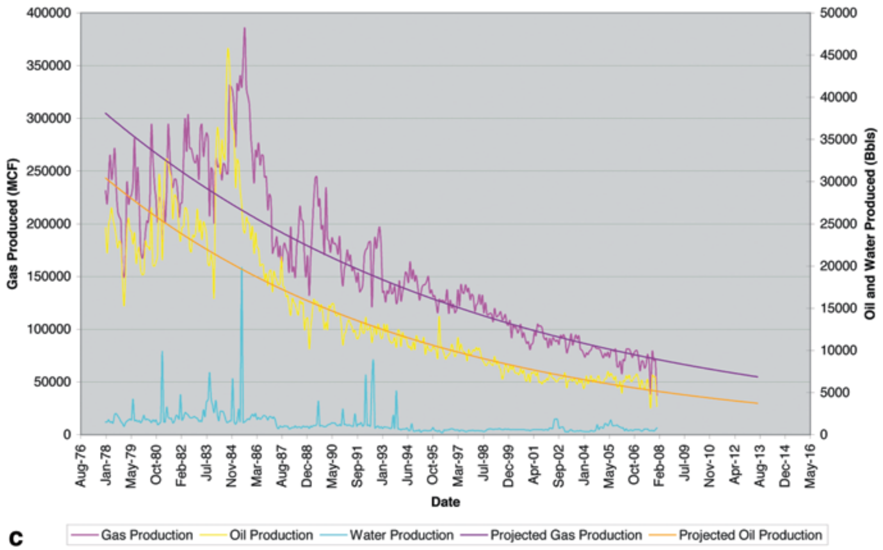


Fig. 12.7 (**a**) Anomalous velocity profile for the Powder River Basin. The transition from normal pressures to anomalous pressures (velocity surface inversion) typically occurs at present-day depths of 8000–9000 ft. The blue area represents a normally pressured, water-dominated, single-phase fluid-flow system, whereas red and green areas indicate anomalously pressured, multiphase fluid-flow systems (i.e., gas-charged). (Modified from Surdam et al. 2005). Oil, gas, and water production decline curves for (**b**) the Amos Draw Complex and (**c**) Kitty Field. The west–east cross section (**d**) through the Amos Draw and Kitty fields displays the pressure regimes within the Muddy Sandstone. The Mowry Shale acts as the primary seal above the Muddy Sandstone, and the Skull Creek Shale seals from below. The Muddy Sandstone is laterally sealed and internally separated into flow compartments by the Roset unconformity. (Reprinted from Bentley and Lusk 2008)



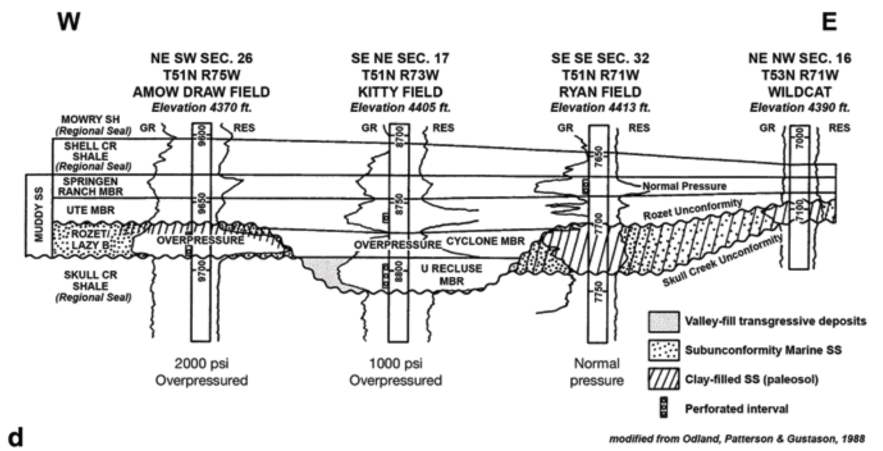


Fig. 12.7 (continued)

Table 12.2 shows preliminary CO_2 storage calculations for the highest-priority potential storage sites (depleted oil/gas fields). The top ten candidate fields have an estimated combined storage capacity of 181.5 Mt CO_2. The numbers shown in Table 12.2 were calculated using USGS methodology (Burruss et al. 2009). The volumetric calculations shown in the table are based on field production numbers and specific reservoir conditions. They probably should be considered conservative estimates of CO_2 storage capacity. Data for the screening process came from the Wyoming Oil and Gas Conservation Commission website, a subscription to IHS

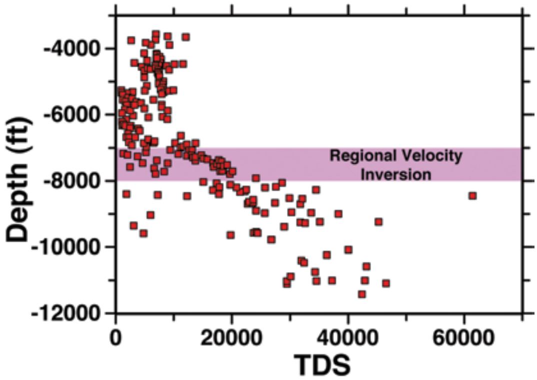


Fig. 12.8 Total dissolved solids (TDS) in formation water from the Muddy Sandstone vs. depth in Wyoming's Powder River Basin. The approximate position of the regional velocity inversion surface is shown. Above this surface, the marine connate waters in the Muddy Sandstone have been diluted; below the surface, there is significantly less, and in most samples, no dilution of the original formation water. (Reprinted from Surdam et al. 2003)

Energy Online, Wyoming Geologic Association Oil and Gas Symposium publications, the National Institute of Standards, and in-house well field data at the Wyoming State Geologic Survey. The top ten depleted fields are distributed over the central basin, with the Amos Draw, Kitty, Horse Creek, and Hilight fields located near open-pit coal mines (Fig. 12.9).

12.2.5 Potential Enhanced Oil Recovery Targets

Enhanced oil recovery (EOR) techniques, particularly CO_2 flooding, are becoming increasingly important to oil production in Wyoming. Since the 1970s, with the exception of a brief period during the mid-1980s, oil production in Wyoming has declined steadily (Fig. 12.10). In 2005, this decline stabilized and oil production leveled off at nearly 60 million barrels per year. So far in the 21st century, enhanced oil recovery (tertiary recovery) and condensate production in the giant Jonah, Pinedale, and Wamsutter gas fields of western Wyoming have offset the still-declining production in the state's older, conventional oil fields. The UW Enhanced Oil Recovery Institute (EORI) estimates that 4.0–8.0 billion barrels of recoverable oil remain in production zones and residual oil zones within Wyoming's depleted oil fields.

Prime EOR targets in the Powder River Basin are the Minnelusa fields in the northeastern part of the basin (Bentley and Lusk 2008). The EORI has determined that the basin hosts approximately 150 of these candidate Minnelusa oil fields, many of which have gone through the secondary water flood stage and appear ideal for tertiary CO_2 miscible flooding. These 150 EOR candidate fields together contained 1.2 billion barrels of original oil in place (OOIP). Use of CO_2 flooding in these fields should recover at least 15 % of the OOIP, or 180 million barrels of oil: at

Table 12.2 Ten depleted fields proposed for potential geologic CO_2 storage, in order of preliminary estimated volumetric capacity

			Reservoir		CO_2 Density			Formation Production		Fm. injection		CO_2 Capacity
Field	Formation	Pressure (psi)	Temp (°F)	Depth (ft)	Kg/m3	Tonnes/m3	Oil (bbls)	Gas (bbls)	Water (bbls)	Water (bbls)	NCV1 (bbls)	tonnes
Hilight	Muddy	4,895	165	9,575	802.57	0.803	76,239,459	296,896,150	267,206,535	240,485,881	399,856,881	51,025,262
Powell	Frontier	8,037	266	12,530	768.60	0.769	20,586,727	261,251,707	742,263	864,192	281,716,505	34,427,842
Hartzog Draw	Shannon	5,000	190	9,183	755.68	0.756	114,363,356	40,640,606	29,346,447	–	184,350,409	22,150,277
Kitty Buck	Muddy	4,397	184	9,210	730.30	0.730	22,274,983	124,759,023	497,472	288,312	147,243,1660	17,097,538
Draw North	Dakota	8,100	280	12,315	752.10	0.752	24,506,580	92,412,871	1,668,288	9,756,6790	108,830,988	13,014,434
Amos Draw (complex)	Muddy	5,590	260	10,052	659.30	0.659	4,760,159	114,477,981	581,463	0	119,819,603	12,560,533
Sand Dunes	Muddy	6,300	240	12,470	733.25	0.733	18,250,679	78,533,694	76,880	1,043,080	95,818,173	11,171,129
House Creek	Sussex	3,241	179	8,257	633.76	0.634	32,614,208	15,600,673	41,489,283	–	89,704,163	9,039,295
Spearhead Ranch	Frontier	7,000	270	12,575	720.12	0.720	5,285,024	49,122,089	88,119	0	54,495,232	6,239,654
Scott	Parkman	3,051	184	8,550	590.72	0.591	17,675,931	26,476,239	8,339,425	2,164,236	50,327,359	4,726,971
											Total	*181.5*

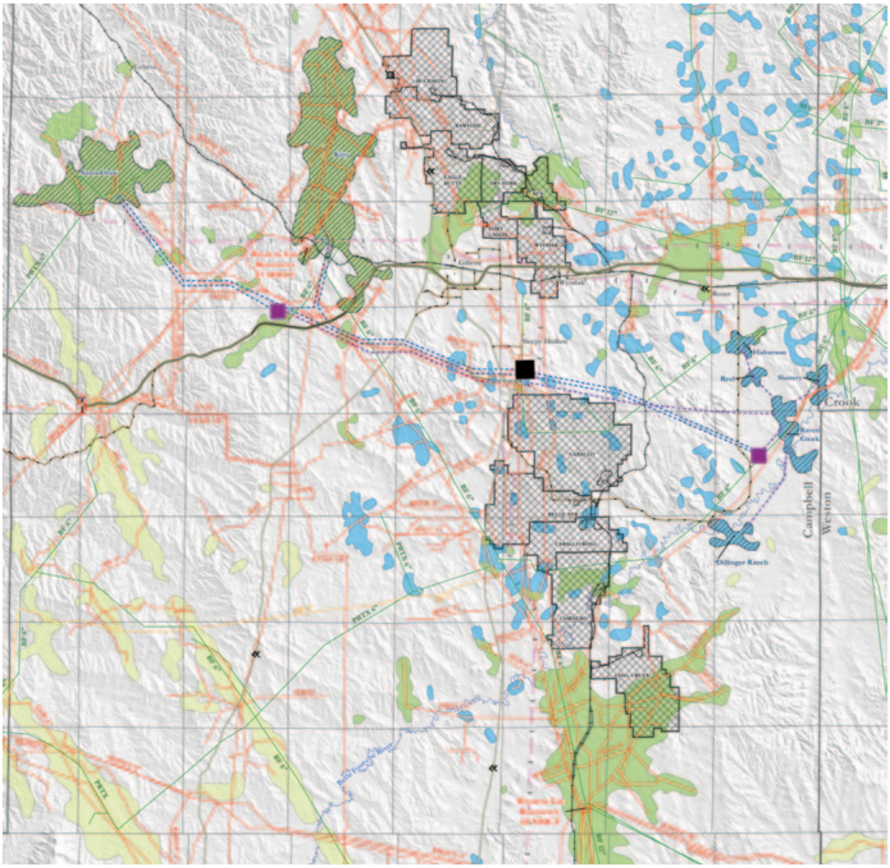


Fig. 12.9 Map of area surrounding Gillette, Wyoming. Cross-hatched areas represent open-pit coal mines, blue areas are depleted Minnelusa oil fields, green areas show depleted anomalously pressured gas fields, and the black dot denotes a potential site for a coal conversion facility. Blue dashed lines are necessary CO_2 pipelines, and red lines are existing hydrocarbon pipelines. Violet squares indicate locations of proposed compressor stations. (Modified from Bentley and Lusk 2008)

US $ 80/barrel, this new EOR production would be worth US $ 14.4 billion. At the required 10 mcf of CO_2 per barrel of recovered oil, it will take 1.8 trillion cubic feet (Tcf) of CO_2 to recover the 180 million barrels of oil. At the very least, the total CO_2 cost (assuming a price of $ 2.00 per Mcf of CO_2) would be $ 3.6 billion. CO_2 cost could be substantially higher for Minnelusa flooding, the final cost depending on supply and demand and the state of delivery infrastructure at the time of purchase.

Two additional aspects of the Minnelusa oil fields in the PRB should be noted. First, the fields (Figs. 12.7b, c and 12.9) are in advanced decline. Second, the potential recoverable tertiary oil reserves in the 150 candidate fields are currently not large enough to support construction of long-range trans-basin pipelines. Therefore, two choices for EOR in the PRB Minnelusa fields remain: (1) acquire a local source of CO_2, or (2) wait for the development of a statewide CO_2 pipeline infrastructure (network) and regional anthropogenic CO_2 storage facilities.

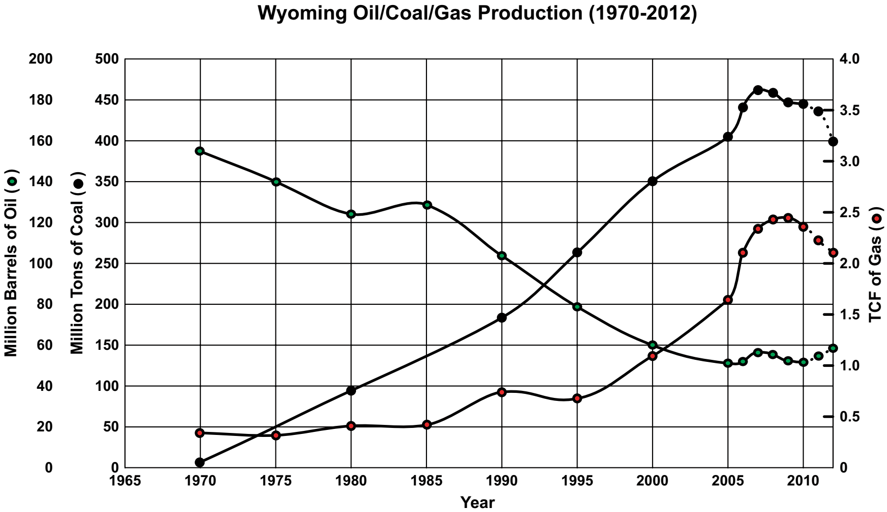


Fig. 12.10 Wyoming coal, natural gas, and oil production from 1970 to 2010. (Modified from Surdam 2007)

12.2.6 Additional PRB CO_2 Storage Capacity

Once the tertiary treatment is complete and the residual oil is recovered from the Minnelusa fields, the fields can then store CO_2. This additional storage capacity will more than double the 181 Mt of estimated storage capacity available in the ten depleted, anomalously pressured gas fields described above (Table 12.2).

12.3 Integrated Energy/Environmental Development Strategy

Five of the six key elements of a future integrated energy/environmental development strategy for the PRB are not only in place, but lie in close spatial proximity to one another (Fig. 12.9). The close proximity of the resource elements is critical to the proposed new development plan, and will minimize development cost, optimize operational efficiency, and effectively reduce the industrial footprint.

The value of the simultaneous multiple-resource approach to energy development in the PRB will be illustrated by describing a potential development scenario that merges all six key elements while reducing environmental degradation and restoring ecological resources. The illustrative scenario that follows is not unique, but flexible and easily modified. Therefore, the detail and general focus in the following discussion should be on the multitude of benefits to Wyoming such an approach delivers.

First, open-pit coal mining would continue using existing extractive technology or newly developed, improved technology as it becomes available. In the future, the coal mined to support the new proposed coal-to-chemical facilities hopefully will offset any decline in coal production caused by the retirement of the oldest and most inefficient conventional coal-fired power plants, followed gradually by the rest of the coal-fired power plant fleet, probably after 2050. Clearly, the retired coal-fired power plants are currently not being replaced by similar new plants, but instead will be replaced by natural gas-fired power plants, some form of integrated combined cycle plant (technologies still under development), renewable energy, nuclear reactors, or some combination of these. One of the aims of the scenario being developed for the PRB is to sustain a strong extractive coal industry in the future. Maintenance of the US $ 1.2 billion contributed annually to the Wyoming economy by the extractive coal industry (Fig. 12.1) is an important aspect of any future PRB energy development plan. The significant increase in product value created by the coal-to-chemical/synfuel industry (Fig. 12.6) will result in far greater state revenues.

Second, the new coal-to-chemical facilities should be located as close to the mines as possible. In Shaanxi Province, China, the coal-to-chemical plants and associated coal mines are sited in the same location – either over underground coal mines or next to open-pit coal mines. Ideally, in Wyoming the mined coal would be transported from the open-pit coal mines to the coal-to-chemical facilities via conveyor belt. This type of transportation eliminates the need for additional rail or truck traffic, both of which contribute to habitat fragmentation and air quality degradation.

Next, the coal-to-chemical/syngas facilities will need access to water resources. As previously described, CBM produced water would best support these coal conversion facilities. The volume of water required to supply the plants will vary depending on facility specifications. In China, the coal-to-methanol plants are designed for a 6:1 ratio of water to product (barrels).

Preliminary calculations suggest that over the next 20 years, the CBM industry will produce one billion barrels of water annually (Surdam et al., 2007). This volume of water, if used at coal-to-chemical plants similar to those in China, would support an annual yield of about 160 million barrels of product. As this new industry grows or the CBM industry slows, the required water resources could be supplemented or replaced by produced and treated water from deep saline aquifers in the basin center (Fig. 12.5b). However, one billion barrels of water would support approximately 40 methanol plants (each producing 700,000 tonnes of methanol annually), or 24 diesel plants similar to those in commercial operation in China (Fig. 12.2). It follows that it would take many decades before a Wyoming coal conversion industry's demand for water would exceed the available CBM water supply.

The problem with the CBM water lies not in the volume available, but in transporting it. The CBM water is scattered and must be collected and then transported to the coal mines. The ideal transport conduit for the water is the Belle Fourche River that runs from the "Big George" CBM area northeast to Keyhole Reservoir (approximately 35 miles east of Gillette; Bentley and Lusk 2008). Keyhole

Reservoir would provide an outstanding storage site for the CBM water prior to use in coal conversion facilities. The obstacle to this route for water transport is a 1943 water compact between Wyoming and South Dakota pertaining to the Belle Fourche River Basin: the compact ensures that almost all unappropriated river water belongs to South Dakota. If this proposed scenario were to include storing water in Keyhole Reservoir, Wyoming would have to negotiate an agreement with South Dakota to establish ownership of CBM water transferred via the Belle Fourche River drainage and stored in Keyhole Reservoir.

An alternative water transportation plan entails building a collection pipeline from Dead Horse (the "Big George" CBM area) to the vicinity of the existing coal mines. Small storage ponds would have to be constructed at each of the coal-to-chemical facilities. More information regarding pipelines that could potentially transport CBM water is available (Surdam et al. 2006).

At this point in the scenario, the resources to support an industrial coal-to-chemical/syngas facility are assembled in the vicinity of an open-pit coal mine, with the plant site as close to the mine as is practical. Thus far, no new mines are required, water resources currently wasted are put to beneficial use, and existing coal conversion technology is deployed. No new environmental impacts will result from any part of the plan, except perhaps from the construction of underground pipelines – and in this case, the disruption would be temporary and mitigated rapidly.

Consider the significance to Wyoming and the U.S. of deploying coal conversion technology. The CBM water produced annually in the PRB could support production of 10 % of the diesel fuel consumed in the nation. Using the Chinese coal-to-diesel technology as a model, 10–20 coal-to-diesel plants in the PRB could produce approximately 150 million barrels of diesel annually (6.3 billion gallons), or 10 % of the nation's yearly diesel consumption. At this rate, a coal-to-diesel industry in the PRB, constrained by available CBM water, could replace 12 days worth of the nation's crude oil imports (currently, the US imports approximately 12 million barrels of crude oil per day).

12.3.1 Carbon Emission Storage

In the following discussion, the typical CO_2 emissions from commercial coal-to-methanol and coal-to-diesel facilities in China are used to derive estimates of CO_2 emissions from a Wyoming coal conversion industry. (Chap. 13 details the coal-to-chemical industry in China's coal-rich Ordos Basin.) A Chinese methanol plant annually uses 2.0 Mt of coal and 6.0 Mt of water, emits 4.0 Mt of CO_2, and generates 0.7 Mt of methanol. A diesel plant annually uses 3.5 Mt of coal and approximately 10 Mt of water, emits 2 Mt of CO_2, and generates 7 million barrels (0.9 Mt) of diesel.

Let us assume that two methanol plants and two diesel plants are built in the initial phase of the establishment of a coal conversion industry in the Powder River Basin (5–10 year timeframe). These plants would generate 1.5 Mt of methanol and 14 million barrels of diesel annually, and would emit 12 Mt of CO_2. In the second phase of coal conversion development (another 5–10 years later), the number of plants could double: four methanol and four diesel plants together emitting 24 Mt of CO_2 annually. The question is this: *how and where can these emissions be stored?* Fortunately, areas of depleted and compartmentalized Cretaceous gas fields (Table 12.2, Fig. 12.9) lie adjacent to the coal mines and proposed mine-mouth coal conversion facilities. The Hilight, Kitty, and Amos Draw depleted gas fields are ideal locations for (1) storage sites for CO_2 emitted by coal conversion facilities on the eastern margin of the PRB, and (2) sources of CO_2 for EOR projects in adjacent depleted Minnelusa oil fields (Fig. 12.9). The total available CO_2 storage capacity of these three fields is approximately 80 Mt (Table 12.2). Potential storage sites for EOR projects in other parts of the basin also exist. These depleted gas fields would initially be used as CO_2 surge tanks to support EOR activities. When the stranded oil in the Minnelusa is recovered, the depleted gas fields could be used for more permanent storage. Using the initial storage site as a surge tank would allow adjacent EOR projects in the Minnelusa fields to have optimal flexibility in designing variable injection rates and in alternating water and CO_2 injection strategies.

12.3.2 CO_2 Utilization

As shown in Fig. 12.9, more than 150 depleted Minnelusa oil fields in the PRB with EOR potential (Bentley and Lusk, 2008) are located near the resource confluence, and are eligible for tertiary recovery via CO_2 flooding. Many have gone through secondary recovery (water flood) and appear ideal for CO_2 miscible flooding. These 150 Minnelusa fields together contained 1.2 billion barrels of original oil in place (OOIP). Typically, CO_2 flooding recovers at least 15 % additional production, or from the Minnelusa fields, 180 million barrels of oil. At the current oil price of approximately $ 80/barrel, the Minnelusa stranded oil would be worth US $ 14.4 billion.

Recovering the stranded oil via CO_2 flooding would require 1.8 trillion cubic feet of CO_2 (10 Mcf per barrel of oil), or 93 Mt of CO_2 (19.3 Mcf/t of CO_2) for the duration of Minnelusa activities. If the EOR project lasted 20 years, the four coal conversion facilities envisioned in phase one of the industrialization (12 Mt of CO_2 emitted annually) would more than adequately support the Minnelusa EOR activities. Importantly, the CO_2 used for the EOR projects would acquire monetary value. A very conservative estimate suggests that, at $ 2/Mcf, about US $ 4 billion worth of CO_2 would be required to recover the 180 million barrels of stranded oil in the Minnelusa. Therefore, a resource typically regarded as a problem with respect to disposal and sequestration would be worth approximately US $ 4 billion in this scenario. Moreover, the Minnelusa fields from which the stranded oil is recovered would be converted to permanent storage sites for CO_2, doubling the 180 Mt of CO_2 storage capacity in the depleted Cretaceous gas fields listed in Table 12.2: at the end of EOR operations, there would be 360 million tonnes of CO_2 storage capacity available to coal conversion facilities.

12.3.3 Benefits of the Integrated Development Approach

Integrated development supports the extractive coal mining industry in the PRB (conventional open-pit technology), and gives monetary value to water produced during CBM development by using it to support a new coal conversion industry in the basin. The proposed scenario involves deployment of mine-mouth coal conversion technology to derive a variety of added-value products from coal. This technology exists and has been tested and improved in China at commercial scale. In China, this coal conversion technology produces methanol, ethanol, acetate, diesel, gasoline, syngas, plastics, and fertilizer.

All coal conversion facilities, unlike conventional coal-fired power plants, inherently capture CO_2. The captured CO_2 can be pressurized at the conversion plant and then transported via pipeline locally as a supercritical fluid. Pipeline transport distances between the coal conversion facilities and storage sites would average 3 km to 8 km (2–5 mi). The CO_2 would be stored in the depleted gas fields and retrieved at variable rates for EOR activities in adjacent Minnelusa oil fields. Enhanced oil recovery projects using CO_2 flooding are characterized by variable demand for CO_2: high rates of CO_2 injection initially, followed by variable demand rates. Commonly, EOR proceeds by alternating water flooding and CO_2 flooding. Also, with 150 eligible Minnelusa fields – some small and some large – numerous CO_2 floods would proceed simultaneously. The depleted gas fields are ideal because the stored CO_2 could be produced at variable rates, pressurized, and transported by a single pipeline to a compressor station in the middle of a Minnelusa oil field swarm. Each individual field and operator would then take delivery of the supercritical CO_2 at the compressor station and arrange for transport through small, temporary pipelines.

At this point, the CO_2 originally generated at the coal conversion facilities is monetized and available for injection/flooding in the depleted Minnelusa oil fields. In the example cited (EOR in the Minnelusa oil fields of the PRB), the CO_2 flooding will recover at least 180 million barrels of stranded oil that would not otherwise be recovered. Once the stranded oil is recovered, the oil fields can provide additional CO_2 storage, doubling the CO_2 storage capacity in the region (depleted gas fields plus depleted oil fields).

The University of Wyoming Enhanced Oil Recovery Institute and the Wyoming State Geologic Survey estimate that Wyoming has 4–8 billion barrels of stranded oil, mostly in the Powder River and Bighorn basins. The strategy outlined in this chapter can serve as a model for the use of anthropogenic CO_2 to recover stranded oil by using the confluence of regional resources to effectively and efficiently sustain resource development with minimal environmental impact.

12.3.3.1 Economic Benefits

The resource development plan outlined in this report would provide many diverse benefits to the state of Wyoming and the energy industry. For example, it would expedite the recovery of stranded oil by providing an anthropogenic source of CO_2. In the case of the depleted Minnelusa fields, that oil at today's price ($ 80/bbl) would be worth US $ 14.4 billion. It would also provide a mechanism to monetize CO_2, a byproduct of the coal conversion industry: in this case, the CO_2 would be worth approximately US $ 4 billion. The anthropogenic CO_2 in the model presented here would not represent a regulated disposal problem, but rather a much sought-after and valuable commodity. The deployment of a coal conversion industry – even at the relatively modest scale described here – would generate US $ 14 billion worth of diesel and methanol in the first five to ten years. If the number of coal conversion facilities doubled in the second 5–10-year period, the products generated would be worth US $ 28 billion. Also important, CBM water in this scenario would no longer be wasted, but would serve instead as a valuable resource put to beneficial use. In brief, the plan includes the deployment of a new resource industry that yields both added-value products and a new and greatly needed source of CO_2. This new source of CO_2 would constitute a valuable commodity rather than an environmental problem: it would be used to recover stranded oil that otherwise might never be recovered. The plan would deploy a new industry, recover bypassed energy resources, minimize environmental impacts, and convert a wasted resource into a valuable commodity. Most importantly, it would sustain resource development opportunities for future Wyoming generations and extend state revenue derived from energy resource industries.

12.3.3.2 Job Creation

The Ordos Basin in Shaanxi Province, China, has many structural and energy resource similarities to the Powder River Basin of northeastern Wyoming. Consider that the Ordos Basin is part of a cratonic platform that developed into a stable basin during the Paleozoic with subsequent tectonic activity dominated by both regional subsidence and uplift. In Shaanxi Province, with the exception of uplifts and depressions that developed at the margins, the Ordos Basin is characterized by a huge monoclinal structure (110,000 km^2) with a 1–2° dip to the west (the Shaanbei Slope).

More than 40 oil fields have been discovered in the Ordos Basin, including the largest oil field discovered in China in the past decade. Four of China's five largest gas fields, with reserves in excess of 100 Bm^3 of gas, are located in the Ordos Basin. The basin also contains 367 Bt of coal reserves, and produces more coal than any other area of China.

The greatest difference between the Powder River Basin and the Ordos Basin is the existence of coal conversion facilities: the Ordos Basin hosts 22 coal-to-methanol plants and one coal-to-diesel plant (with one additional plant approved but not yet constructed), while the PRB has no significant coal conversion facilities, but a multitude of large open-pit coal mines. In the Ordos Basin, the 22 coal-to-methanol plants produce more than 10 million tons of methanol, use 30–40 million tons of coal, require 110 Mt of water, and emit 42 Mt of CO_2 annually. These numbers do not include the coal and water necessary to generate the electricity required by the coal conversion plants (typically from coal-fired power generation), or the amount of CO_2 emitted by the power-generating facilities.

Most importantly, each of the coal conversion plants employs approximately 400 workers, so the 22 plants in the Ordos Basin provide approximately 9,000 jobs. During the construction phase, the number of jobs provided would be much higher. In summary, a network of coal conversion plants in the Powder River Basin would substantially aid in reversing the current trend of coal-related job loss in northeastern Wyoming, while providing value-added domestic products derived from coal.

12.3.4 Environmental Impacts

The proposed integrated energy development strategy will not only benefit Wyoming economically, but will do so without causing any new significant negative environmental impacts. In fact, one could argue that the scenario's implementation would have several positive environmental effects, including a reduction in CO_2 emissions and an end to the current waste of CBM produced groundwater and its associated negative effects on streams and pastureland. Most significantly, the proposed strategy will occur entirely on existing developed lands already subject to habitat destruction and fragmentation (coal mines, oil and gas fields): the strategy will have no new negative developmental or ecological consequences, will not expand the footprint of energy development in the state, will not exploit or degrade lands and habitat currently untouched by energy development, and will not exacerbate the impact of existing energy development in the basin. This is particularly important given the potential listing of the sage grouse (*Centrocercus urophasianus*) under the Endangered Species Act. Extensive sage grouse habitat spans the PRB, and Wyoming is seeking ways to facilitate energy development while avoiding further declines in grouse populations that could trigger listing of the species and cripple the state's energy industry. The integrated strategy outlined here would dovetail nicely with the state's efforts. Relatively minor environmental impacts caused by the construction of small pipelines will be temporary and mitigated to the greatest extent possible (pipelines installed underground and routed along existing transportation corridors such as county roads, etc.). In addition, existing facilities and infrastructure would be upgraded and streamlined to further minimize environmental impacts.

12.4 Conclusions

The energy development plan presented in this chapter focuses on the future synchronous development of resources in the Powder River Basin. The example used to illustrate the benefits of such an approach is based on the confluence of a set of natural resources in the Powder River Basin, but the approach itself is flexible and could be tailored to fit other Wyoming and many Rocky Mountain basins. This approach emphasizes synergistic relationships among resource elements in order to optimize the effective and efficient exploitation of the state's energy resources while minimizing environmental degradation. The fundamental idea is that it is more effective and efficient to develop a set of resource elements together systematically rather than separately.

In the systematic approach, a contentious problem associated with the development of one resource becomes part of a useful solution in the development of another. Until now, resource development in Wyoming has often tended to focus on one particular resource at the expense of others, an approach designed to maximize short-term economic benefits rather than ensure long-term economic sustainability. The state has the opportunity today to try something new: the approach described in this chapter will foster open resource management discussions and compromises, improve education and long-term planning, and build positive, collaborative relationships among different resource industries rather than perpetuate a single-resource mindset. Most importantly for future generations, the innovative resource development strategy outlined in this report will help achieve long-term sustainable use of Wyoming's energy and environmental resources while maintaining state revenues derived from natural resources.

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