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Future Energy: Opportunities and Challenges

Part II. Energy Sources

Chapter 13. Energy Transport

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Future Energy: Opportunities and Challenges

Thomas W. Kerlin



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Energy Transport

The Main Points

- Energy and materials used for providing energy are rarely produced where they are used.
- Most coal moves from mines to power plants in trains.
- Pipelines provide the most efficient and economical way to move liquid and gaseous fuels.
- The U.S. has extensive pipelines for liquids (crude oil and petroleum products) and gases (natural gas and propane).
- Existing pipelines are unsuitable for ethanol and hydrogen.
- High-voltage electrical transmission is used to reduce energy losses.
- Foreign-sourced liquid and gaseous fuels are transported in large ships.
- Large increases in the extent and capacity of the electrical transmission and distribution system will be needed in the future.
- Energy transport systems impact the environment, eliciting major opposition to their construction.
- Future electrical transmission and distribution systems will be more efficient than current systems because of the implementation of “Smart Grid” principles.
- The U.S. must make a large investment in energy transport for the future.

13.1 Introduction

Usable energy and the materials used as sources of usable energy are rarely produced at the location where they are used. The transport of energy and of the raw materials needed to produce energy incurs large expenditures of money and energy and causes environmental impacts that elicit opposition. These are major considerations in ensuring a transport system that adequately serves energy needs in the future.

13.2 Coal Transport

More than 90 percent of the coal used in the U.S. is used by electric power plants and steel mills. Coal mining occurs principally in the west, in the Midwest, and in Appalachia.

There is a trade-off in using coal to produce electricity, as to whether it is better to produce electricity near the mines (in mine-mouth power plants) and transport that electricity to users, or to haul coal to power plants located near users. Consumers prefer that coal-fueled power plants, and their associated pollution, be located far away. But electrical transmission losses, cost, and public acceptance of transmission lines, grid reliability, and stability concerns, access to sufficient cooling water, and utility business models are all factors in deciding on plant siting.

In 2002, coal traveled from mines to users by train (65 percent), trucks (13 percent), conveyer belt and slurry pipeline (10 percent), and barge (12 percent).¹

13.3 Liquid Fuel Transport

13.3.1 Oil-Based Fuels

The transport of oil-based liquid fuels begins with the movement of oil from wells to refineries. The distances involved may be short, as in some

sites in Texas and California where wells and refineries are close to one another, but wells and refineries are usually far from one another. Also, America increasingly depends on oil and oil products imported from distant sources. This oil travels from the wells to tanker ships or to refineries that process the oil before loading it onto ships. The ships offload the crude oil or refined products at U.S. seaports.

Pipelines provide the most economical way to transport liquid fuels. The U.S. has around 150,000 miles of pipeline for carrying crude oil and refined products².

Oil-based liquid fuels include gasoline, diesel fuel, jet fuel, and fuel oil. In the U.S., these liquids move from domestic refineries or seaports to regional distribution terminals via pipelines that crisscross the country. The terminals store the liquid fuels. Tanker trucks then carry the fuels to retailers (such as filling stations) or to end users.

Liquid fuels made from oil sands or oil shale may become important in the future. If this occurs, new pipelines will be needed to transport fuel from processing facilities located near the resource deposits, which exist in regions that are not currently served by pipelines. This includes pipelines for bringing oil sand products from Canada to the U.S.

This complex transport system, composed of ships, pipelines, and trucks, must operate smoothly and consistently if liquid fuels are to be available when and where needed. A breakdown in any part of the transport chain can cause major disruptions.

13.3.2 Liquid Biofuels

If liquid biofuels grow into a major energy source, their transport will require new infrastructure. The first reason for this is the anticipated location of biofuel production facilities. Biofuel production facilities will have much smaller throughputs than oil refineries and will be dispersed throughout growing regions in order to minimize hauling distances for the biomass. Gathering liquid biofuels from biorefineries will require a transport system

that serves many widely spaced refineries, each with a much smaller production rate than an oil refinery. As with oil-based liquid fuels, the most efficient way to transport liquid biofuels to distribution terminals is via pipelines. However, existing pipelines do not adequately serve major anticipated biofuel production regions. In addition, current pipelines are unsuitable for ethanol transport. Pipelines for ethanol, the biofuel that currently dominates development efforts, must be free of water because ethanol, unlike hydrocarbons, will absorb water or other contaminants in pipelines, with resulting degradation of the ethanol's suitability as a fuel.

After the liquid biofuel reaches distribution terminals, it would be stored and then carried by truck to retailers and users in the same fashion as hydrocarbon fuels are carried.

13.4 Gaseous Fuel Transport

13.4.1 Natural Gas

Pipelines are used to carry natural gas from wells to users. The gas pipeline system in the U.S. includes around 1.5 million miles of pipes of various sizes¹. The main components of the system are³:

- Gathering lines: Small diameter pipes carry gas from the wells to a gas processing plant.
- Processing plants: These facilities separate out the condensable gases (propane and butane) and impurities.
- Mainline transmission systems: Large diameter pipelines carry gas to market areas.
- Market hubs/centers: Locations where pipelines intersect and gas flows are routed.

- **Underground storage facilities:** Underground reservoirs are used to store natural gas. Since changes in gas consumption cannot be matched quickly by changes in gas flow from distant wells, gas flows from nearby reservoirs are used to provide needed gas. Reservoirs are filled during low-demand periods and drained during high-demand periods. About 400 underground storage facilities exist in the U.S. Depleted oil and gas wells and salt caverns can serve as reservoirs.
- **Liquefied gas systems:** Stored liquefied gas (natural gas and propane) provides reserves that can be re-gasified and injected into the pipeline when needed to help satisfy demand. There are around 100 liquefied gas storage systems in the U.S.
- **Local distribution lines** to homes, businesses, and industries.

Natural gas demand experiences daily and seasonal variations. Demand is highest in the cold winter months. Gas suppliers implement measures to ensure that supply capability matches demand. Utilities may stop service to users who agree to interruptible service in return for lower gas prices. Matching supply to demand may also be accomplished by drawing gas from stored reserves.

Pipelines are economical only when supplied by a region with large gas reserves. Natural gas also occurs in smaller quantities in many locations in the U.S. Because it is uneconomical to provide transport facilities for small gas resources, the gas is usually called “stranded gas.” On-site liquefaction is sometimes employed to facilitate transport. Using these small gas resources for local heating or small-scale electricity production is possible, but uncommon.

As with liquid hydrocarbons, natural gas is also imported. Huge ships carry natural gas in the liquefied state. Liquefaction requires cooling the gas to temperatures below its liquefaction temperature (-259°F) and keeping it cold until returning it to the gaseous state and feeding it into pipelines.

13.4.2 Propane

Propane is also an important gaseous fuel. Propane is obtained by separation from natural gas and as a by-product of oil refining. These sources contribute to domestic production in about equal quantities. Imports provide about 10 percent of U.S. propane. Propane, unlike natural gas, liquefies at normal temperature and modestly elevated pressure. Consequently, liquid propane provides a concentrated energy source that occupies a small volume and is easily transported. Propane serves home energy needs in areas not served by natural gas lines. It also serves specialized functions such as home barbeque fuel where small, portable tanks store the propane.

Pipelines carry gaseous propane throughout the U.S. in a network covering over 70,000 miles⁴. The propane arrives at distribution centers, where it is pressurized into the liquid state and stored. Special trucks with pressurized tanks carry propane to users, where it is transferred into pressurized tanks.

13.4.3 Hydrogen

Hydrogen is under consideration as a fuel for major deployment in the future. Hydrogen will likely be produced by the electrolysis of water. Water electrolysis can occur in large, centralized production facilities or in small, decentralized facilities close to the point of use. The transport issue is whether to transport hydrogen or to transport electricity for local hydrogen production.

Hydrogen transport and storage are more difficult than natural gas transport and storage. The difficulty is due mainly to two properties of hydrogen (see Chapter 12):

- Because of the small size of hydrogen molecules, it diffuses through metals that are impervious to other gases.
- Hydrogen causes embrittlement in high strength steel and alloys containing nickel and titanium

Because of these effects, the existing infrastructure for natural gas transport and storage cannot be used for hydrogen. Technology for hydrogen transport and storage is available, but the infrastructure that would be needed for a large hydrogen energy economy based on centralized production would have to be built anew and at considerable expense. Decentralized hydrogen production would shift the problem from transporting and storing hydrogen to that of transporting electricity to the production site.

13.5 Electricity Transport

13.5.1 The Electrical Power System

The electrical power system consists of producers, power lines, and auxiliary equipment such as transformers to increase or decrease voltage, switches and circuit breakers to allow or prevent the passage of current, and devices to control the timing of voltages and currents (characterized by the power factor discussed below). The system is huge, with thousands of producers and hundreds of thousands of miles of power lines.

The U.S. electrical power system is about to experience major changes that include the following:

- The system will be required to deliver much more energy as electricity becomes the preferred form of energy in America.
- The mix of producers will change as America reduces fossil fuel use and increases the use of wind, solar, geothermal, hydroenergy, and, possibly, nuclear sources.
- The intermittency of solar and wind sources will require that the system has the ability to compensate for frequent and sudden changes in production from these sources.

- The size and characteristics of the electricity transport system will change. More power lines and new, efficiency-increasing technology will be needed to provide greater carrying capacity.
- Changes in equipment and use patterns at the consumer end to permit greater efficiencies, improved reliability, and lower costs for electrical energy will occur.

Electricity transport is unique in that its production must match demand continuously and instantaneously. This balance is achieved in an electrical system that includes base-load producers, load-following producers, and producers of opportunity (see below).

Base-load plants are generally those whose economics or limited ability to change power output rapidly favor operating at constant power. Having low operating costs relative to capital cost usually favors base-load operation. For example, since nuclear plants have low operating costs relative to capital costs, utilities usually prefer to operate them as base-load producers.

Load-following plants are those that increase or decrease their generation as needed to maintain a balance between production and consumption. Load-following plants must be able to change generation quickly. Low capital costs are important in load-following plants because they operate at zero or reduced power much of the time, producing no return or reduced return on investment. Gas turbine power plants are important providers of load-following capability.

Producers of opportunity operate whenever the facility is capable of producing power. Some power plants can provide clean energy with low operating costs, but their power output is controlled by nature. Examples are solar power and wind power. Generally, it is desirable to use all of the energy that these systems can deliver and to use other producers in the system to compensate for power production changes imposed by nature.

The electrical network consists of many interconnected producers and consumers. Changes in production or consumption anywhere in the network

are felt throughout the network unless they are restricted by controllers on segments of the transmission system. Consequently, the sudden shutdown or startup of a large power plant or large consumer facility triggers immediate control action to re-establish a balance. (Legend has it that a fisherman drowned in Tennessee because water flow through a dam increased suddenly to compensate for the shutdown of a power plant in Illinois.)

The electrical system must be capable of satisfying demand at all times, including periods of peak demand. Consequently some plants are often idle or are producing below capacity. Older, dirtier, less efficient plants are often used when needed to contribute to peak production. Having adequate capacity to satisfy peak loads forces utilities to have plants that will see only part-time service. Reducing peak loads, and thereby reducing the need for part-time plants, reduces the required investment for utilities.

Steps taken to reduce energy demand peaking are called load leveling. Demand-side (user) steps can help with load leveling. Inducements (usually economic) to operate electrical equipment when overall demand is low can reduce peak demand. For example, one utility offered free water heaters to customers who would accept utility-initiated periods of inoperation.

On the supply side, one load-leveling approach is energy storage. During periods of low demand, utilities can use excess generation capacity to power facilities such as pumped storage systems, batteries, or hydrogen production and storage systems to capture energy for release during subsequent high demand periods.

Energy storage is also often mentioned as a way to deal with the intermittency of wind and solar power. As long as intermittent sources supply a small fraction of total electrical demand, it is desirable to feed all of their production into the grid. If power from intermittent sources either exceeds power demand or causes excessive demands for changing energy flows in the grid, storage becomes desirable. Of course, the added facilities for energy storage add to the cost of electricity from the intermittent sources, and some energy losses inevitably occur in the transformations from electricity to stored energy and back from stored energy to electricity.

13.5.2 Electricity Transmission and Distribution

Electricity flows from the power plant into the transmission network, and from the transmission network into the distribution network. Transmission refers to the transfer of bulk quantities of electricity from power plants to distributors. Distribution refers to the transfer of electricity from distributors to users.

Electricity transmission may be done via direct current (DC) or alternating current (AC). Almost all transmission is AC. A major advantage of AC over DC is that simple devices called transformers can be used to increase or decrease AC voltage, but not DC voltage.

Transmission networks use high voltages to reduce losses of energy in the transmission lines. Power delivery is equal to the product of voltage and current. AC transformers change voltages and currents without changing power delivery (except for some losses due to heating in the transformer). A transformer causes a change in current that is inversely proportional to a change in voltage. For example, doubling the voltage halves the current, and the power remains unchanged.

The advantage of using high voltages and low currents in transmission of electricity is that this approach reduces energy losses due to resistance heating of the conductors. Electrical heating, called Joule heating, increases with the square of the current:

$$P_J = I^2 R \quad (13-1)$$

where

P_J	=	Joule heating power
I	=	electrical current
R	=	electrical resistance

For example, halving the current flowing through a transmission line will reduce Joule heating by a factor of four. High-voltage transmission line voltages are typically 110,000 volts and higher. Since such high voltages are not

suitable for end users, distributors use step-down transformers to reduce voltage. Losses due to transmission line heating amount to a bit over 7 percent of U.S. electrical energy consumption.

The frequency of the alternating current produced by a turbine-generator is determined by the rotational speed of the turbine shaft. The rotational speed depends on the difference between the rate at which energy is delivered to the turbine blades by the working fluid and the rate at which the shaft's rotational energy is converted to electricity in the generator. If the turbine power exceeds the generator power demand, the shaft rotational speed increases, and the frequency of the electricity increases. The reverse occurs if generator power demand exceeds turbine power.

For many reasons, the frequency of the electricity produced must be maintained within close limits. Since turbine shaft speed and the frequency of the electricity produced change immediately following imbalances between power production and power demand, maintaining constant shaft speed and frequency is the goal of power plant control systems. The modern network maintains the electrical frequency very close to 60 Hertz (cycles per second) in the U.S. electric power system.

Some components in an AC electrical network cause a phase shift between voltage and current. That is, the waveforms for the oscillating voltages and currents are displaced relative to one another. Maximum useful power is delivered only when voltage and current are in phase with one another (no displacement between the wave forms of current and voltage). When they are not in phase, the circuit is carrying current that does not contribute to usable power. As a result, there are greater heating losses in the transmission lines for the same rate of delivery of usable power than would occur if the voltage and current were in phase. A term called the *power factor* is defined as the usable power divided by the power that would be delivered if voltage and current were in phase with one another. Components are installed in electrical networks to cause the power factor to be as high as practical, with a power factor of 1 being the goal.

13.5.3 The Smart Grid

Planners are now preparing for a much larger and more efficient electrical system for the future. The new system is called the Smart Grid⁵. While in the past, the term “grid” usually referred to the power lines and auxiliary equipment used to transport electricity, the “Smart Grid” encompasses the transmission and distribution systems and the users.

The Smart Grid is not a simple concept that can be explained in a few words, but the basic idea is to use computers and information technology to monitor and control electrical systems and, thereby, improve efficiency, reliability, and cost. The U.S. Department of Energy provides the following definition of the properties of the Smart Grid⁵:

- Self-healing from power disturbance events
- Enabling active participation by consumers in demand response
- Operating resiliently against physical and cyber attack
- Providing power quality for twenty-first century needs
- Accommodating all generation and storage options
- Enabling new products, services, and markets
- Optimizing assets and operating efficiently

Some of these features are to be implemented by utilities. Information technology will provide indications of existing and incipient component malfunctions or sub-optimal operation. The grid’s characteristics will be designed for robustness, and grid management will employ optimal control, continuous monitoring, and problem mitigation strategies to achieve reliable and efficient delivery of electrical energy.

Interestingly, some benefits of the smart grid will involve actions by the consumer as well. Many of these actions will focus on consumer activities that contribute to load leveling and distributed electricity production. Smart meters that enable time-of-use pricing will encourage consumption during times of non-peak demand, when electricity costs charged by some utilities are lower. For example, water heating and battery charging for electric and plug-in hybrid vehicles at night rather than during the day, when power demand is higher, will help to reduce peak demand. Another interesting option is an air conditioning system that makes ice at night when non-peak power is available⁶. The ice later provides daytime cooling.

Consumers can also become producers. As local electricity production (mainly with solar photovoltaic systems but with some contribution from wind turbines) increases, these devices can reverse the traditional flow of electricity and feed any excess power into the grid. Some even envision the use of stored energy in vehicle batteries to feed the grid during peak load periods. This approach is called vehicle-to-grid or v2g. However, the impact on battery life and the need to save the stored energy for use in vehicle propulsion will probably limit v2g power generation to emergency situations.

13.6 Environmental Issues

Energy transport requires construction of facilities that are objectionable to many citizens. Concerns include potential damage to the environment and undesirable aesthetic effects. For example some citizens are concerned about disruption of land during pipeline construction and possible leaks after operation begins, and electric power lines alter the landscape in a way that is distasteful to many citizens. Thus, there is an unavoidable conflict between a desire to leave things as they are and accepting changes in order to have the energy needed to sustain society.

13.7 Overview

America must upgrade its energy transport infrastructure to accommodate increases in energy consumption and changes in the ways that energy is produced and consumed. Expanding and improving America's energy transport system will require great effort and expense, whether the transported quantity is coal, liquid, gas, or electricity. For each of these transport systems, there will be debate about the benefits versus the financial, environmental, and aesthetic costs. The creation of a new energy transport infrastructure is a looming problem whose resolution will be determined by political as well as technical and economic considerations.

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Exercises

- 13-1. Hauling coal by train consumes around 362 BTU per ton mile. How much energy is used in the U.S. per year to haul coal if the average haul is 1,000 miles?
- 13-2. The U.S. has around 157,000 miles of high voltage power lines. Building new lines costs around \$1 million per mile. If the U.S. has to double the size of its electrical transmission system in order to handle a doubling of electricity use, estimate how much will have to be spent for high voltage lines. If new power plants cost around \$3,000 per kilowatt, how do the costs of new high voltage lines compare with the cost of new power plants?
- 13-3. What is the dollar value of annual U.S. electrical transmission losses if electricity is worth 11 cents per kilowatt-hour?

