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Alice J. Friedemann

When Trucks Stop Running

Energy and the Future of Transportation

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Preface: Running on Empty

Even as a child, I was interested in oil. When I was 10 years old, Dad drove us into the hot oven of Death Valley in a dark blue car with black seats and no air-conditioning. We were being cooked alive. The gas gauge crept toward empty for what seemed like hours. I thought, for sure, we were going to run out of gas. Cockroaches may be able to survive this heat, but I am not a bug! I will never forget finally pulling into the gas station, the drinking fountain getting ever closer until, at last, I felt the delicious chill of water in my throat. Dad gassed up the car, and all was well with the world.

A decade later, it looked like civilization itself was running on empty as the energy crisis of 1973 took over our lives. I was in college, and joined an alternate technology group. We watched engineers build electric cars, windmills, and convert a car to run on methanol. I got to help build a solar collector by drinking beer and painting the cans black. Saving the planet was not only going to be fun, it was going to be a party!

It wasn't long before non-OPEC oil was found and the Mideast turned their oil tap back on, and I stopped worrying about energy. Renewable power was on the way and the "evil" oil companies wouldn't be able to stop it. My grandfather, Professor Francis J. Pettijohn, was a seminal figure in sedimentary geology. Sedimentary basins—that is where you find oil! Grandfather would try to educate me about the energy density of oil and the high hurdles blocking the path of alternate energy, but it wasn't until I read his memoir that my world view of running the planet on beer-can solar power changed. That's when I discovered that Grandpa had been a friend and mentor of M. King Hubbert, who predicted world peak oil production around the year 2000.

Yikes! It *was* 2000. Had oil peaked yet? An Internet search led to a Pandora's box of Jay Hanson's die-off website, Yahoo group energy resources, and years later attending Association for the Study of Peak Oil conferences. I was a science writer and shifted my focus from natural history to energy-related topics, and have since then read hundreds of books and thousands of articles on energy from within the U.C. Berkeley library system.

Earlier in my life, to pay the mortgage I designed and architected software systems, which I learned how to do at Electronic Data Systems after rigorous training in analysis and assembler programming working on the Medicare system, followed by a stint at Bank of America in the check processing division, and finally 22 years at American President Lines (APL). As a systems engineer, you need to have both a "big picture" and detailed understanding of the business framework before designing a new system. Inevitably, everything is connected.

APL was a global shipping line that also routed cargo on trucks and trains as well as helped customers with logistics, especially just-in-time freight and the fastest, most reliable delivery times possible within a continuous intermodal flow of containers across ships, trains, and trucks. APL was a leader in transportation and had the most extensive container ship system in the U.S. by the late 1960s, and partnered with rail to start the StackTrain service, containers stacked double high on railcars, tremendously increasing the efficiency of trains and reducing fuel consumption.

All of the APL computer systems needed to be up 24 × 7, everywhere, or ships, trucks, and trains would stop as Bills of Lading, manifests, and dozens of other legal documents could not be produced. Around the clock, everything from military supplies for the 1991 Gulf War to running shoes was kept on the move with as little waiting time as possible between modes of transportation.

When a new project came along, I needed to understand how long it would take and how many staff were needed to make sure an "improvement" didn't cost more than the money saved. This is very much like the "energy returned on invested analysis" performed to make sure more fossil energy isn't invested than returned on a given technology or project.

In business, this kind of analysis is essential to prevent bankruptcy. Yet when scientists find oil, coal, and natural gas production likely to peak within decades, rather than centuries, or that ethanol, solar photovoltaic, tar sands, oil shale, and other alternative energy resources have a low or even negative energy return on the energy invested, they are ignored and called pessimists, no matter how solid their findings. For every one of their peer-reviewed papers, there are thousands of positive press releases with breakthroughs that never pan out, and economists promising perpetual growth and energy independence. Optimism is more important than facts. And, it's essential for attracting investors.

Civilization as we know it depends on our global transportation system of ships, trains, and trucks, all of which are fueled by oil. Since oil reserves are finite, one day supplies will be diminished to where the cost of moving freight and goods with our present oil-fueled fleet will not pencil out. We have an oil glut in 2015 and a corresponding lack of urgency. Yet, inevitably the day will come when oil supplies decline. What will we do? What are our options? That is the sobering reality this book will explore.

Using my transportation knowledge and the analytical skills I learned during my 27-year career as a systems engineer, my science background (B.S. in Biology with a Chemistry and Physics minor from the University of Illinois), and what I have learned over what is now 15 years of energy research, I will look at the vulnerabilities of our current commercial transportation sector.

Everything in our homes, everything in our stores, got there on a truck at some point. Before that, many of those goods also were transported by ship and/or train.

Come the day that oil is no longer abundant and affordable, will the millions of trucks that make our way of life possible be able to keep on running? I'll look at the energy scenarios that could disrupt trucking, followed by overviews of the roles and respective energy efficiency of ships, railroads, and trucks—the three modes of heavy-duty transportation essential to keeping industrial civilization running. After that there are three chapters on oil: how invisible yet necessary it is, peak oil risks, and the distribution of liquid fuels. Then the viability of alternative fuels that are already commercially developed to replace oil is considered: biofuels, hydrogen, natural gas, and liquefied coal. Another way transportation might continue without a diesel fuel substitute is electrification with batteries or overhead wires, the subject of the next chapters. If electricity is to be used to power transportation, then it is important to understand the issues that need to be solved as we migrate towards a 100 % renewable electric grid as fossil fuels decline. Finally I look at other issues that will affect transportation such as climate change, at U.S. government energy policy since the first energy crisis in 1973, and then conclude with how I see the road ahead.

This book is very United States-centric, because the U.S. uses the most oil of any nation, is the most dependent on oil for transportation, and will be the most affected by oil decline. America is also the military superpower that keeps oil flowing from the Middle East (or at least thinks it does), where two-thirds of the remaining oil lies, to Europe and Asia. Finally, the U.S. is where I live.

We live in the Oil Age, and as oil declines, our lives will change. Eyes wide open, this book explores the way forward.

The book would need to be many hundreds of pages to cover commercial and noncommercial energy technology as much as I'd like, but more information can be found at my website, www.energyskeptic.com.

Acknowledgments

I am especially grateful to my husband Jeffery Kahn for his help with this book. Every morning over the breakfast table, as we read the morning newspapers, discussions would break out that inevitably (and unrelentingly!) focused on energy transportation. Great debates occur regularly at our breakfast table! Jeffery served as my sounding board. He pushed me to stick to my original intent, which was not to write a textbook for energy experts, but an inviting book for the curious of mind, the public citizen, and the many among us who passionately care about our future. I hope this is what I have done.

When I finished the book, Jeffery tirelessly read and reread my endless revisions, and his comments and wonderful sense of humor helped me enliven parts of the book. Jeffery's many years as a science journalist at Lawrence Berkeley National Laboratory was also invaluable in helping me see when I hadn't explained a concept well enough.

I am also thankful to Charles Hall, who gave me the opportunity to write this book and to be part of his outstanding energy series. Charles Hall is a pioneer in the field of energy resources and systems ecology. He is an academic hero of mine, and an enduring inspiration to look deeper, be willing to challenge conventional wisdom, and ask the troubling, unasked questions.

Finally, thanks to Marianne Betterly for help with editing and the many years of hosting a writing salon, each accompanied by a fabulous meal. Marianne also fed me constant encouragement, and that helped keep me running.

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About the Author

Alice J. Friedemann is the creator of http://energyskeptic.com/. Ms. Friedemann is perhaps best known for "Peak Soil," which David Pimentel at Cornell, Tad Patzek at U.C. Berkeley, and Walter Youngquist (author of "Geodestinies") edited.

When push comes to shove! The last resort, as demonstrated by author Alice J. Friedemann!

Chapter 1
When Trucks Stop Running, America Stops

Trucks aren't going to all stop running at the same time as in a dystopian movie or novel. But since fossil fuels are finite, if a renewable way to run trucks isn't found, they will stop. As a thought experiment to appreciate how important trucks are, let's look at what would happen if they all stopped. What follows are just a few of the consequences described in Holcomb's (2006) *When Trucks Stop, America Stops*, McKinnon's (2004) *Life without Lorries*, and SARHC's (2009) *A Week without Truck Transport*.

Day 1: One or more deliveries of produce, fresh meat, beer, chilled goods, fresh bread, and dairy products are made to grocery stores, schools, restaurants, and hospitals every day. With such frequent arrivals, there are no inventories, and these goods would disappear the first or second day. For example, hospitals can get syringes, catheters, and clean linen with hours of ordering them, so they have little inventory, and would run out quickly if deliveries were disrupted, according to Al Cook, former president of the Materials Management Association. Businesses relying on many daily deliveries begin to run out of various items. Construction slows down as materials required aren't delivered.

Day 2: Panic and hoarding begin to empty most grocery store shelves, restaurants and pharmacies close, construction stops, garbage starts to pile up fast and creates a health hazard, especially at hospitals. Businesses depending on just-in-time delivery start to lay off workers, especially in the auto industry or from lack of packaging. Pharmacies get deliveries every day and are already running out of some medicines.

Day 3: Widespread layoffs begin. Sewage treatment plant sludge and slime storage tanks are now full and wastewater sludge can no longer be trucked to a landfill or incinerator or bio-solids to farms. Mass transit is scarce, infrastructure repair and essential services like police, fire, ambulance, telecommunications, utilities, and mail last as long as private fleet tanks have diesel. Banks move billions of dollars of cash, coins, and checks to check clearing centers. Within a few days, ATMs will run out of cash, causing major problems for those without bank accounts and credit cards.

Day 4: Most service stations have fuel deliveries 2–3 times a week, and so they are out of fuel now. The repercussions start to reverberate globally, as 48,000 imported containers per day can't be unloaded off of ships nor can export

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containers be loaded in the U.S. With no fuel, airplanes and railroads shut down, and garbage is piling up everywhere, 685,000 tons of trash each and every day in the U.S.

Day 5: Industrial production ends, a large proportion of the labor force is laid-off or unable to get to work, travel and recreation stop, health care is confined to emergency services, and livestock begins to suffer from lack of feed deliveries.

Day 7: Many cars are out of gasoline, and many people will be unable to get to work, shop for food, or get medical care. Hospitals will begin to run out of oxygen supplies.

Two weeks: Clean water supplies will begin to run dry as trucks are unable to deliver purification chemicals. Only boiled water will be safe to drink.

Within four weeks: Hospitals have 30 days or less of drugs, vaccines, insulin, surgery anesthetics, and blood products due to reliance on just-in-time deliveries. Erin Fox at the Salt Lake City hospital said that “the supply chain is horribly thin” (Wysocki et al. 2006). If farm tractors are unable to harvest crops they will rot in the fields. Department of Defense supply chains will break down, crippling the military “in ways no adversary has been able to achieve.”

After 1–2 months: Coal stockpiles at 40 % of coal power plants run out from lack of rail, truck, and barge delivery (EIA 2015), causing blackouts in regions most dependent on coal power generation. About five percent of the compressors moving natural gas through pipelines are electric, so natural gas power plants connected to these electricity-dependent pipelines will stop operating as well (DOE 2015). In a blackout, fuel pumps for vehicles, ships, and railroads stop, because they use electricity. Refineries also depend on electricity to make gasoline and diesel to get trucks moving again.

No, trucks aren’t going to all stop running at once. But the scenario reveals how utterly dependent we are on trucks. And it brings home a hidden truth which bears repeating: Everything in our homes, everything in our stores, got there on a truck at some point.

The scenario also hints at an interdependency. National Academy Engineer Paul H. Gilbert describes this interdependency as “Our basic infrastructure systems include our electric power, food, and water supplies, waste disposal, natural gas, communications, transportation, petroleum products, shelter, employment, medical support and emergency services, and facilities to meet all our basic needs. These are a highly integrated, mutually dependent, heavily utilized mix of components that provide us with vitally needed services and life support. While all these elements are essential to our economy and our well-being, only one has the unique impact, if lost, of causing all the others to either be seriously degraded or completely lost. And that, of course, is electric power. Our technically advanced society is literally hard-wired to a firm, reliable electric supply” (House 108-23 2003).

While it seems extremely unlikely that anything like this would occur in the U.S., there are precedents. Some examples of real-world situations where oil has been cut off include:

- In North Korea, trucks did stop running in 1991 when Russia cut oil supplies by 90 %. Crops weren't planted, coal mining and coal-based fertilizer production ended, and the coal-based electric grid blacked-out, so irrigation water couldn't be pumped. In the end, the result was famine (Williams et al. 2002).
- Russia cut off the oil supply to Cuba in 1988. Cuba abruptly had no fuel, fertilizer, or pesticides for agriculture, or the ability to import food due to the absence of foreign exchange. People began to go hungry and Cuba was rapidly approaching collapse (OXFAM 2001).
- When railroads stopped running after 9/11 to guard hazardous materials, in only two days the city of Los Angeles was out of chlorine and faced the threat of no drinking water (House 108-23 2003).

Scenarios in which oil supplies could be greatly reduced in the U.S. over a short period include a war in the Middle East, war or terrorist blocking of the Straits of Hormuz or Straits of Mallaca, terrorist or other destruction of refineries. World oil is produced in about 500 refineries (the U.S. has 135 of them, with half of refining done in the hurricane vulnerable Gulf coast states of Texas and Louisiana).

We hate trucks when they turn freeways into parking lots, and detest their toxic fumes and emissions. But "love 'em or hate 'em", we can't live without 'em. When trucks stop running, we stop too.

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Chapter 2
Shipping Makes the World Go Round

From Sail to Steamships

Until fossil fuels arrived, wood from forests determined the wealth and power of nations. Trees were the energy source that industry used to make iron, glass, brick, and ceramics; the fuel to heat and cook with, and also the material for homes, barns, furniture, tools, fences, barrels, wagons, and hundreds of other products (Perlin 2005; Conners 2002). No wonder Paul Bunyan was a superhero!

A large seventeenth century sailing vessel was constructed with enormous amounts of wood, about 2000 oaks from 50 acres. A billion acres of forests made America rich, since European forests were greatly depleted, especially of the tall, straight mast trees needed for battle and merchant ships.

For many centuries, wooden sailing ships went about 4–6 knots on average (4.6–7 mph). If winds were not good, voyages could be very slow. Hell on Earth was being abandoned by the winds in the horse latitudes. It took the Mayflower 66 days in 1620 to travel the 3236 miles between Southampton, England and Boston, Massachusetts, at an average speed of 1.77 knots (2 mph) (MQ 2003). By the 1850s, Clipper sailing ships could go as fast as 20 knots in good winds, but averaged about 5–8 knots (5.8–9.2 mph) over long distances (Spilman 2012).

The ability to utilize water transportation and especially to exploit the energy of winds was extremely important to the development of earlier commerce, since a ship could carry many times as much cargo as any land-based system (Cottrell 2009).

In the nineteenth century, steam-powered boats of wood, and later iron and steel, dominated river, lake, and eventually ocean traffic because they could carry a great deal more cargo and travel faster than sailboats. By 1840, steamboats burned about 900,000 cords of wood in the U.S., 20 % of all fuel-wood sold, stopping every two hours to refuel their huge boilers.

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In the eighteenth century, nearly everyone in America lived near coasts and navigable lakes and rivers, because it was cheaper to move a ton of cargo across the Atlantic on a ship than 30 miles inland over land (McPherson 1988).

Warehouses, factories, and workers were located and lived near ports to lower costs. Millions of workers and horses drove, dragged, and pushed cargo through city streets to and from piers, where cargo sat in warehouses along the dock. Items were counted and recorded, then dragged to the side of the ship, carried up gangplanks, and tightly secured in the hold, since loose cargo knocking around could sink a poorly loaded ship in rough seas.

At the next port it was all hauled out onto the dock, where buyers looked for their shipments, customs inspectors opened each box to assess duties, carpenters fixed damaged crates, and clerks inspected each label, moving cargo destined for other ports into a transit shed, and then reloaded for shipment to the next port, where the process was repeated. Is it any wonder: Labor was as much as 75 % of the total cost of moving goods by sea.

Once steamships began burning coal in the 1850s, more and more of them were made of iron. As the decades passed, the speed, size of ships, and amount of cargo carried accelerated dramatically.

The Container Ship Revolution

In 1956, containerization really took off when Malcom McLean bought a steamship line and altered a large ship to hold containers of standard dimensions, the same size his truck fleet carried. These containers could seamlessly and efficiently be transferred between truck and ship with no need to unload the contents. This radically reduced transport costs due to less labor needed, warehousing, port congestion, loading and unloading time, and less damage or theft. The stevedore's loss was the world's gain.

In 1965, dockworkers could load only 3750 pounds on a ship per hour. Today, in the container ship era, we load 18 times that weight per hour—66,000 pounds of cargo with far fewer laborers, in just hours rather than week(s). Ships that are 1300-feet-long ply the seas carrying up to 18,000 20-foot containers piled 20 high. These leviathan ships have created a smaller world, erasing geographic barriers. The role of containerization in global trade can be clearly seen in Fig. 2.1 (Economist 2013).

Without containers and very large fuel-efficient ships, there would be no globalization. Ships can move 38,580 short tons of cargo 3000 miles across the Atlantic cheaper than a truck can carry that much weight just 180 miles (ECORYS 2009).

Containerization meant that goods were packed just once and lifted onto trains, trucks, and ships interchangeably. Ships could load and unload in just a few hours instead of a week or more.

Today the U.S. has 360 commercial ports, kept open by dredging. Every year, 400 million cubic yards are dug out of navigation channels, berths, and private

Fig. 2.1 Thinking inside the box. *Sources* World Trade organization; US Bureau of Labour Statistics; Bernhofen et al. (2013); Economist (2013)

Table 2.1 Growth of shipping from 1970 to 2012

Type of ship	Max tons per voyage	Average mph	Million tons per year 1970	Million tons per year 2012
Container Ship	195,000	24–29	90	1498
Bulk carrier	400,000	11.5–17	1165	4567
Oil tanker	510,000	11.5–15	1440	2796

Source Stopford (2010), UNCTAD (2012)

terminals. If this dredged material were laid out between New York and Los Angeles, it would be 20 feet deep and as wide as a four-lane freeway (AAPA 2015).

Containerization accelerated the movement of factories and farms to the cheapest locations for labor and land. Many businesses began to depend on long, complex supply chains from countries around the world instead of locally made parts and goods.

In addition to container ships, bulk carriers that haul coal, ore, grain, and other commodities, and oil tanker vessels have revolutionized global shipping. The scale of change, as shown in Table 2.1, is staggering. Wooden sailing ships once carried 300–1000 tons (Stopford 2010) at 5–9 miles per hour (mph) whereas ships today can carry as much 510,000 tons at greater speeds as shown in Table 2.1.

Ninety Percent of Global Trade Is Carried by Ships and Barges

Pound for pound and mile for mile, today's ships are the most energy-efficient way to move freight. Table 2.2 shows the energy efficiency of different modes of transport by kilojoules of energy used to carry one ton of cargo a kilometer (KJ/tkm). As you can see, water and rail are literally tons and tons—orders of magnitude—more energy efficient than trucks and air transportation.

Table 2.2 Energy efficiency of transportation in kilojoules/ton/kilometer

Kilojoules of energy used to carry one ton of cargo one kilometer	Transportation mode
50	Oil tankers and bulk cargo ships
100–150	Smaller cargo ships
250–600	Trains
360	Barge
2000–4000	Trucks
30,000	Air freight
55,000	Helicopter

Source Smil (2013), Ashby (2015)

Ships use marine diesel engines that can attain efficiencies over 50 % (AASHTO 2013; Smil 2013) and used just 10 % of global transportation oil to carry 8.8 billion tons of cargo in 2012.

In 2009 in the U.S. by weight, 60 % of the cargo carried by ships and barges was energy products: 46 % oil and petroleum products, 13.2 % coal, and 1.2 % fertilizer (U.S. Census 2012).

Although trucks don't appear impressive in Table 2.2, they waste 10.3 times less oil than cars when you consider how many tons can be hauled per gallon of gas (ton-mpg). The National Research Council estimates the average auto gets 15 ton-mpg and the average class 8b truck 155 ton-mpg (NRC 2010; Table 2.1). If average truck mileage can be increased from 6.5 to 12.5 mpg, trucks could get 275 ton-mpg (Mele 2009). Already, with today's technology, trucks are capable of getting 10 mpg, so this is within reach.

Air freight, by comparison, is a gluttonous use of fuel, energy that could be more efficiently used by trucks, rail, and ships. It is likely that when oil begins to decline, so will this mode of transport. This will free up 7 % of transportation fuel for trucks and locomotives, since jet fuel is similar to diesel in crude oil refinery processing.

Conclusion

In 1957 nearly a third of freight moved by water, now only 4 % does, despite more than half of Americans living in coastal counties. This is despite ships and barges being orders of magnitude more energy efficient than air freight and trucks, and despite 25,000 miles of navigable rivers, coastal waters, lakes, and canals (NFRCP 2010).

How could this happen? The reason is simple. Cheap oil and the $425 billion (2006 dollars) 47,800 mile interstate highway system enabled trucks to provide faster door-to-door service. In the 1980s, just-in-time deliveries began, reducing fuel efficiency even further since trucks often arrive partly-full with just the goods needed, and may return empty (see Fig. 2.2). Fast service on taxpayer-subsidized

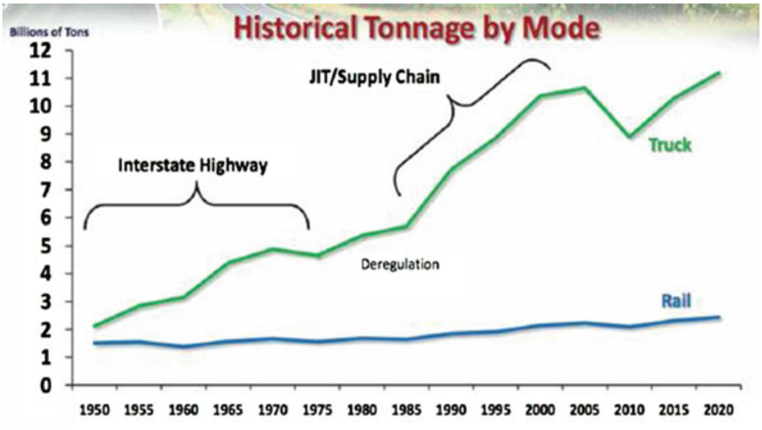

Fig. 2.2 Historical tonnage by mode: billions of tons 1950–2020. *Source* NRC (2014)

roads made water and rail transport less able to compete with trucks, despite their much better fuel efficiency.

We've traded away energy to gain time. We've traded away our energy security for getting stuff as soon as possible. Do we really have to have it RIGHT NOW?

Allowing such waste reflects a short-sighted U.S. energy policy that encourages quick returns on investment over the longer-term goal of making finite oil last longer.

There are many studies on how to improve marine transportation's share of freight, but without a major transformation of the transportation system it is hard to see how ships and barges could compete with trucks. To do this would require major changes, such as shifting funds from roads to the marine highway system (and rail). Furthermore, oil prices need to be much higher. This could be done with oil taxes to pay for maintenance and upgrades to the marine highway system, which is falling apart, and to encourage Americans to buy fuel-efficient vehicles.

Waiting for oil shortages to force the price of oil up is a bit like an alcoholic waiting until the tremors, psychotic hallucinations, and disorientation of delirium tremens starts before putting the bottle down. It is a bit late in the game.

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Chapter 3
Why You Should Love Trains

Trains Consume Less Fuel yet Carry More Goods Than Trucks

Trains rock and roll around three or more times as fuel efficiently as trucks. Trains use just one gallon to move a ton 476 miles, using just 2 % of U.S. transportation fuel (USDOT 2012).

Trucks move one ton 69 to 133 ton-miles per gallon. Rail to truck efficiency ratios range from 1.9 to 5.5 for double-stack trains, with containers two levels high (USDOT 2009).

Rail and road fuel efficiency varies by how level the journey is, by cargo weight, and speed. A unit train, which hauls a single commodity like coal from origin to destination, can get as much as 856 ton-miles per gallon in the flat Midwest, or as little as 445 in the mountainous west. Truck efficiency varies quite a bit too, making comparisons difficult. For example, a non-unit train might only be 2.1 times as efficient as a 9-axle truck, but a unit train could be 5.3 times more efficient than a five-axle truck (Tolliver et al. 2013).

Rail hauled 16 % of the 11.7 billion tons of freight that moved across America in 2012, carrying it 3.3 trillion miles. But since the average train shipment travels 811 miles, and trucks just 216 miles, trains ended up carrying more freight by weight than trucks in ton-miles (one ton of freight transported one mile). Overall, trains accounted for 45 % of ton-miles, versus 38 % for trucks (USDOT 2014).

It bears repeating: Trains did this with just 2 % of transportation oil, while trucks used 22 % (Davis et al. 2014).

Since 1980, railroads have doubled their efficiency (in ton-miles), with double stacked containers and unit trains, lighter railcars, better train control systems, wheel and rail lubrication, training engineers to drive better, and computer software. Trains aren't standing still. In the future, even more gains will be made as old locomotives are replaced with new, more efficient ones.

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A Brief History of Railroads

Starting in the 1800s, trains reduced famines, because for the first time, large amounts of food could be delivered quickly to inland regions where crops had failed (Fagan 2000). Once the British–built rail system in India was completed, famines, that were once common, essentially disappeared, since crop failures were always a regional, not national event.

In the U.S., the era of the Iron Horse began in the 1820s in the northeast. By 1850 there were 9000 miles of tracks, and by 1880, railroads employed more people than any other industry besides agriculture. In 1890 there were nearly 164,000 miles of tracks, thanks largely to the 180 million acres of free land granted to railway companies by states and the federal government between 1855 and 1872, which made millions of acres available for settlement. By 1869, rail stretched from the Atlantic to the Pacific. One hundred years later, we landed a man on the moon. But long before that, rail made American manifest destiny possible.

Rail quickly displaced less energy efficient and slower river steamboats and canal barges. Able to operate year round, trains could travel far from the limits imposed by miles of frozen canals and rivers.

But the glory days of rail ended after World War II. Many went bankrupt after the interstate highway system and expanding road networks were built. Fuel was cheap, and trucks can go door-to-door. Oil was so cheap even highly inefficient airplanes gained business at the expense of rail.

In 1920, there were 380,000 route miles of tracks in the U.S. (Route miles refers to the miles of tracks between towns and cities. Route miles don't include parallel tracks, just as you wouldn't quadruple the miles of highway on a four-lane road). Rail is disappearing. Today there are only a quarter of the number of route miles, about 95,000, on the major routes of the seven class 1 railroads that move freight long distances around the country.

There are an additional 45,000 miles of shorter distance tracks run by the 500 shortline class 2 and 3 rail companies. Shortline rail moves commodities like grain, coal, steel, and lumber to mainline rail, which distributes the freight across the nation, and for export.

In the U.S., we've lost 285,000 miles of rail. The country is spidered with rusty rail lines, and nobody seems to have noticed their abandonment. It's a shame, since trains are more efficient than trucks.

Trains move energy itself. Half of the tons hauled by trains are energy or goods made directly from fossil fuels: coal 40 %, refined oil and coke, 2.6 %, tight oil 2.2 %, ethanol 1.5 %, plastics 2 %, and petrochemicals 1 %.

The Powder River Basin in Wyoming supplies 42 % of U.S. coal, and most of this relatively low-energy coal is hauled hundreds of miles to the east coast. This is a big waste since coal plants were designed to burn higher-quality coal, and Wyoming coal is 30 % water—a huge waste of diesel fuel to haul that much water weight (Makansi 2007). On the other hand it is downhill from Wyoming to most anywhere else.

So Why Not Build More Railroad Tracks to Conserve Oil?

For every 10 % of truck freight switched to rail, a billion gallons of fuel are saved.

In 2015 traffic congestion on our roads cost us $160 billion from seven billion hours of delays and the three billion gallons of fuel wasted (TTI 2015). Trains can take trucks off the road, and alleviate congestion. A 100-car train carrying 10,000 tons of freight would get 333 30-ton trucks off the road. Freight rail also emits far less greenhouse gases. Of the 27 % of U.S. greenhouse gas emissions attributable to transportation, locomotives contribute 2.3 % while trucking accounts for 22.9 % (EPA 2015).

Who's Going to Pay for It?

Railroads are privately owned. Roads and highways are built with public tax dollars. Railroads build and maintain the rails on their own dime. So, unlike trucks, barges, and airlines, private freight rail does not receive government taxes or subsidies. Federal aid to railroads is likely to be opposed by other powerful interests such as the trucking industry, road construction, and businesses heavily reliant on trucks. Rather than help out the railroads, they would prefer to increase maximum allowable truck weight and length.

Rail is not especially profitable, since 40 % of rail revenue is plowed back into capital expenditures and maintenance. From 1980 to 2014, America's freight railroads spent $575 billion to maintain, improve, and expand their rail network. The average manufacturer spends 3 % of revenue on capital expenditures, but railroads spend 19 %—over six times more. Rail is consequently less profitable and does not have billions to spend on expanding their route miles (AAR 2015).

Adding more miles of rail capacity is an expensive risk and takes 3–10 years of designing, permits, and building. In 2012 railroads spent $64.1 billion: $42.1 billion running the railroad with fuel and wages accounting for half of that, $8.9 billion on maintenance, and $13.1 billion on growth. Here are just a few of the Class 1 rail expenses (class 2 and 3 shortline rail costs are not included below) (AAR 2013):

- $11.6 billion for 3.7 billion gallons of fuel to move cargo 1.7 trillion ton-miles
- $2.3 billion for 665 new and 258 rebuilt locomotives
- $2.7 billion to add 42,000 tons of new rail
- $4.2 billion on materials to maintain and repair 25,000 locomotives, 374,000 freight cars, 160,000 miles of track, 15.6 million crossties, replace 5800 miles of rail, maintenance of roadway, rail, ties, ballast, and communications
- $1.9 billion on building terminals, tunnels, elevated structures, wharves, and so on
- $1.8 billion to add 650,000 new crossties
- $1.2 billion on signals, positive train controls
- $1 billion on ballast—the rocky bed of railroad ties and tracks

- $850 million for 1601 new and 7673 used freight cars
- $600 million to maintain 100,000 railroad bridges
- $400 million for lubricants and other materials
- $350 million equipment—$100 million highway equipment, $250 million track maintenance equipment, snow plows, shop machinery, boats to maintain bridges
- $300 million computer equipment
- $150 million on land to build railroad terminals, rail line additions, and buildings

If the funding money could be found, there are hundreds of rail projects ready to go (AASHTO 2002; EC 2011; FDOT 2002; USDOT 2010, 2014; Keith 2013; USGAO 2008; Vigrass 2007), such as:

- Get rid of roads that cross railroad tracks by relocating tracks or putting in bridges and underpasses so neither trains or highway vehicles have to stop.
- Heighten tunnels and bridges for stack trains, which carry twice as much cargo (containers are stacked two levels high).
- Improve bridges, tunnels, and class 2 and 3 rail to handle heavier trains.
- Put in shortline tracks between ports and major distribution centers, or along corridors heavily traveled by trucks, and where warehouses and manufacturing are concentrated (especially on unused brownfield land).
- Add double tracks in mountainous regions of the west coast to get long-haul trucks off of the I-5 corridor from California to Washington.
- Divert cargo from trucks to rail or water by adding or improving intermodal connections and terminals, etc., (i.e. transflow, transload, hook-and-haul, and ro-ro/open technology, rail-to-barge).
- Increase the number of trains by adding a parallel track or more sidings where trains can wait for another to pass, positive train control systems so trains can't run into each other and can be spaced more closely.
- Reduce distance traveled by punching tunnels through hills and mountains.
- Get rid of curved tracks to increase longevity. Heavily used curved tracks last 8–12 years but straight tracks can last 90 years.
- Add train yards out of the way of through traffic.
- Add more route miles of tracks if existing right-of-ways still exist (and prevent other developers from buying these right-of-ways and putting them to other uses).

Conclusion

Disappearing rail is a trend that ought to be reversed. Regional rail will become increasingly important as a way to reduce fuel consumption. To kickstart this, state government grants and subsidies could boost local economies by increasing the miles of shortline rail. Incentives for warehouses and businesses to move next to shortline rail would reduce truck traffic on roads, and allow some rural roads to return to gravel, reducing the oil needed for road maintenance.

Trains consume just 2 % of transportation fuel yet carry more ton-miles of vital freight than trucks, which consume 20 % of transportation fuel. Come the day that oil is less abundant, we'll all wish there were more miles of rail tracks.

But until transportation policy makers and politicians make reducing oil consumption their driving goal, things are not likely to change.

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Chapter 4
Why You Should Love Trucks

Nearly everything in our modern world was on a truck, even if only for the last mile: the furnishings and building materials in every home, store, office, and factory, the food you eat, from planting and harvest to stove-top and dinner plate, and even the asphalt and concrete in the roads that trucks travel on.

In other words, we are alive because of trucks. If trucks ever stopped running, we'd all become Amish overnight.

Trucks are mind-bogglingly varied in size, shape, and task. Buses, fire trucks, bulldozers, tractors, harvesters, concrete trucks, cranes, dump trucks, garbage trucks, log carriers, goliath mining trucks, refrigerated trucks, tank trucks, delivery trucks, freight trucks … there is no end to the work that trucks perform for us.

When I say truck, I am not referring to class 2 light trucks like pickups, which use 13.2 % of U.S. transportation fuels. Rather, I am referring to the class 3–8 trucks in Table 4.1. These are the medium class 3–6 delivery, mail, cherry picker (bucket) trucks that use 4.6 % of transportation fuel, as well as the heavy-duty class 7–8b cement, bus, tow, garbage, fire, and four-axle trucks hauling freight on highways that consume 19 % of fuel. There are even higher classes of trucks, such as the five-axle (class 9) and seven-axle multi-trailer class 13 trucks. Altogether, there are many kinds of mainly diesel engine trucks and equipment used in agriculture, mining, oil and gas, construction, roads, logging, industry, fire, deliveries, hauling goods and garbage, and all the other essential services that make civilization possible.

When railroads were built, human settlements became less dependent on vessels for shipping, and inland populations grew, especially in towns and cities near railroad depots.

After World War II cheap oil made it possible to build distant suburbs and towns across the nation, connected by 4.1 million miles of roads. Now, people can live just about anywhere inland, so much so that four out of five communities depend entirely on trucks for all of their goods (ATA 2015). Virtually no one in these communities realize this. They are truck towns.

Clearly it would be better if ships, barges, and rail delivered goods across the map since they're far more energy efficient. But with only 25,000 miles of marine highway and 95,000 route miles of rail tracks, ships and rail can't compete with the four million miles of roads trucks travel on. Trucks dominate goods moving less

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Table 4.1 Comparing light-duty vehicles with medium- and heavy-duty vehicles

Class, application	Annual fuel (billion gallons)	% of fuel used	Annual fleet miles (billion)	Gross max weight	2006 number of vehicles	Typical mpg range 2007	Ton-mpg
1c, car	74,979	42.2	1682	6000	135,000,000	25–33	15
1t, small SUV	37,400	21.1	813	6000	70,000,000	20–25	17
2a, large SUV	18,000	10.1	305	8500	23,000,000	20–21	26
2b, van	5500	3.1	93	10,000	6,200,000	10–15	26
3, utility van	1462	0.8	12	14,000	690,000	8–13	30
4, delivery	533	0.3	4	16,000	290,000	7–12	42
5, bucket	258	0.1	2	19,500	170,000	6–12	39
6, school bus	6020	3.4	41	26,000	1,710,000	5–12	49
7, tow, refuse	1926	1.1	9	33,000	180,000	4–8	55
8a, dump	3509	2.0	12	80,000	430,000	2–6	115
8b, 18-wheeler	28,075	15.8	142	80,000	1,720,000	4–8	155
Total	177,662		3115		239,390,000		

Source (NRC 2010 Table 2.1, p. 35)

than 550 miles because it is usually faster, cheaper, and easier to deliver by truck, door-to-door. Eighty percentage of cargo goes less than 550 miles, and a truck can deliver that in a day. So that makes it tough to shift a lot of freight from trucks to rail or ships (Brogan et al. 2013). Even when rail is less expensive, trucks are often preferred for just-in-time, valuable, perishable, and fragile goods.

Today's global economy—where materials and components are sourced from all over the world before being assembled—would be inconceivable without the global transportation system. Trucks do a lot of the heavy lifting.

Take the case of an auto engine. Where do they come from? The supply chain for engines might involve 22 trucks from origin to destination. For example, **12 trucks** from different suppliers deliver the parts for an engine to a factory in Japan. Assembled engines are loaded onto a **truck** and taken to the port of Tokyo, where the container is lifted by a **crane** onto a ship, unloaded by a **crane** in Oakland, taken to a yard by a **reacher-stacker (RS) truck** to wait for a train, loaded onto a rail car by an **RS truck**, unloaded in a Detroit suburb by an **RS truck** and put on an **18-wheeler** bound for a distribution center, where the engines are taken out by **forklift** and reloaded into **two smaller delivery trucks** for delivery to an auto factory in Detroit.

That's nothing compared to Apple's supply chain, which has over 200 suppliers in 361 locations across 25 countries, delivered just-in-time to the factory assembling the final Apple computers and phones (Apple 2015). Each supplier has suppliers, beginning with the minerals and plastics the other parts are made from—all put together, like a giant Russian nested doll, into a finished product.

This mobile manufacturing miracle has its cost. Just-in-time supply chains waste a lot of fuel. To deliver only what is needed, trucks arrive more frequently, half-full, and often return partly or completely empty. On the other hand less energy is required to build and maintain storage buildings.

When trucks are full, they often don't carry their full weight. About 60 % of trucks fill up with goods before they reach their maximum load weight (Bradley et al. 2009). Often this is due to bulky packaging, though this can be reduced. For example, Hamburger Helper made their curly noodles flat, which shrank the carton 20 %, saving Walmart 500 truck deliveries a year (Forbis 2008).

Over the past few decades, truck fuel efficiency was doubled in the U.S., but trucks drove more miles, so total fuel consumption didn't decrease. This was due to the rebound effect, also known as Jevon's paradox, which occurs when efficiency is improved. So if a better engine allows a truck to go twice as far using half as much fuel, a truck driver is likely to drive twice as far, and oil consumption is not reduced.

Medium and heavy trucks burn 22 % of U.S. transportation fuel. This could be reduced by 33–50 % with better engines, tires, weight reduction, driver training, hybrid power trains, aerodynamics, longer or double trailers, better logistics, and other enhancements depending on how the truck is used (NRC 2010; HDT 2014). On the other hand, many of these changes would themselves require energy, for capital costs or retiring otherwise perfectly good capital equipment early.

These improvements could shift up to 10 % of cargo from rail to truck, with little benefit, since heavy trucks cause so much road damage. Right now, truck fees cover only 20–50 % of the damage trucks do to roads, with taxpayers stuck picking up the rest of the bill. This makes trucks appear to be less expensive than they are, shifting some cargo from energy-efficient rail and ships to trucks (Parry et al. 2014).

Trucks already have a huge monetary advantage over privately funded rail and poorly-funded maritime transport because the government spends $146 billion on building and maintaining roads every year.

This shift away from energy efficiency will increase if a consortium of industries succeeds in raising maximum truck weight to 97,000 pounds from the current 80,000 (CTP 2015). If that happens, up to 20 % of rail cargo might shift to trucks, and even more if truck lengths increase (NPC 2012). The extra weight would cause 50–63 % more damage to roads and bridges costing $65 billion, on top of the existing $200 billion in repairs needed, resulting in eight million more heavy trucks on rural roads. Country roads are not built to withstand even 80,000 pounds (CRS 2012; FHWA 2000; Hjort et al. 2008; House 113-36 2013; Swift 2012; USDOE 2008; USDOT 2000).

Conclusion

The American way of life sprawls along four million miles of roads. This remarkable web of asphalt may not be sustainable. In "The Big Roads", Swift (2012) explores the history of the 47,000 mile federal interstate highway system. He concludes that since vehicles are so dependent on oil, our four million miles of roads will be a spectacular waste of money if new fuel sources aren't found.

The subsequent chapters look at what makes the world go round, oil, on how oil became integral to civilization as we know it, and after that, what other fuels could propel diesel engines when oil begins its inevitable decline. Especially what could fuel trucks, since everything in our fossil-fueled civilization, including the electric grid, depends on them.

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Chapter 5
The Oiliness of Everything: Invisible Oil and Energy Payback Time

Just as fish swim in water, but are essentially unaware of it, we swim in oil. You can't understand the predicament we're in until you can see the oil that saturates every single aspect of our life. To illustrate how energy permeates society, let's look at the life cycle of a simple object, the pencil. I've condensed and reworded Leonard Read's 1958 essay *I Pencil, My Family Tree* to show the fossil fuel energy inputs with ***Energy-Using ACTIONS Italicized*** and **objects** **made with energy underlined**. As you read each italic and underlined word, think energy.

> My family tree begins with … a Cedar tree from Oregon. Now contemplate the antecedents—all the people, numberless skills, and fabrication: All the **saws**, **trucks**, **rope**, and **other gear** to ***HARVEST*** and ***CART*** cedar logs to the **railroad** **siding**. The ***MINING*** of ore, ***MAKING*** of **steel**, and its ***REFINEMENT*** into **saws**, **axes, and** **motors**. The ***GROWING*** of **hemp,** and bringing it through all the stages to heavy and strong **rope**. **The** ***BUILDING*** of **logging camps** (**beds**, **mess halls**). ***SHOPPING***, ***DELIVERY***, and ***COOKING*** **food** to feed the working men.
>
> The **logs** are ***SHIPPED*** to a **mill** in California. Can you imagine how many people were needed to ***MAKE*** **flat cars**, **rails, &** **railroad engines?**
>
> At the **mill**, cedar logs are ***CUT*** into pencil-length slats, ***KILN-DRIED, TINTED, WAXED,*** and ***KILN-DRIED*** again. Think of all the ***EFFORT*** to make the **tint** and the **kilns**, ***SUPPLY*** the ***HEAT***, ***LIGHT***, and ***POWER***, the **belts**, **motors**, and all the **other things** a **mill** requires. Plus the men who ***POURED*** the **concrete** for the **dam** of a **hydro-electric plant** which ***GENERATES*** the mill's ***POWER***! Don't overlook the workers who have a hand in ***TRANSPORTING*** **60** **train-cars** of **slats** ***ACROSS*** the nation.
>
> Once in the **pencil factory**—worth millions of dollars in **machinery** and **buildings**—each slat has **8 grooves** ***CUT*** into them by a **groove-cutting machine**, then the **lead-laying machine** ***PLACES*** a piece of **lead** in every other slat, ***APPLIES*** **glue** and ***PLACES*** another **slat** on top—a lead sandwich that's mechanically ***CARVED*** into seven pencils. My "lead" is **graphite** ***MINED*** in Sri Lanka.

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Consider the miners and those who ***MAKE*** their **tools** and **paper sacks** in which the graphite is ***SHIPPED*** and those who ***MAKE*** the **string** to ***TIE*** the **sacks** and the men who ***LIFT*** them aboard **ships** and who ***MAKE*** the **ships**. Even **lighthouse keepers** and **harbor pilots** assisted in my birth.

The **graphite** is mixed with **clay** ***FROM*** Mississippi with **ammonium hydroxide** in the ***REFINING*** process. Then **wetting agents** and **animal fats** are ***CHEMICALLY REACTED*** with **sulfuric acid**. After ***PASSING THROUGH*** **many machines**, the mixture appears as endless extrusions as from a sausage grinder, ***CUT*** to size, ***DRIED***, and ***BAKED*** for several hours at **1850 °F**. The leads are ***TREATED*** with a ***HEATED*** mixture of **candelilla wax** ***FROM*** Mexico, **hydrogenated fats**, and **paraffin wax**. My cedar ***RECEIVES*** six coats of **lacquer**, with ***REFINED*** **castor oil**. Observe the **labeling**, a film ***FORMED*** by ***APPLYING HEAT*** to **carbon black** mixed with **resins**.

My bit of **metal**—the ferrule—is **brass**. Think of all the **persons** who ***MINE*** **zinc** and **copper** and ***MAKE*** **sheet brass**. Those black rings on my ferrule are black **nickel**. Then there's my crowning glory, the **eraser**, made by ***REACTING*** **rape-seed oil** ***FROM*** Indonesia with **sulfur chloride**, and numerous **vulcanizing** and **accelerating agents**. The **pumice** comes ***FROM*** Italy; and the pigment which gives "the plug" its color is **cadmium sulfide**.

Does anyone wish to challenge my assertion that no single person on the face of this earth knows how to make me? Millions have had a hand in my creation, no one of whom knows more than a few of the others. There isn't a single person who contributes more than an infinitesimal bit of know-how. Yet neither the miner nor the logger can be dispensed with, any more than the chemist at the factory or the worker in the oil field—paraffin being a by-product of petroleum. I, Pencil, am a complex combination of miracles: a tree, zinc, copper, graphite, PETROLEUM and so on."

If pencils are swimming in oil, think of the energy embodied in a wind turbine with its 8000 parts coming from hundreds of suppliers around the world, the roads over which hundreds of trucks arrive with workers, cement, rebar, and turbine parts, and the hundreds of miles of transmission wires, towers, and substations the electricity travels over. I, Wind Turbine, would be thousands of pages long.

Every year, the world uses one cubic mile of oil. What would it take to replace that? Well, you could build 52 nuclear power plants every year, for 50 years. Or any one of the other options, every year, for 50 years (Goldstein 2007):

- 4 Three Gorges Dams (18,000 MW), OR
- 52 nuclear power plants (1100 MW), OR
- 104 coal-fired power plants (500 MW), OR

- 32,850 wind turbines, (1.65 MW), OR
- 91,250,000 rooftop solar PV panels (2.1 kW panel)

Any of these would take 50 years to replace ONE year's worth of oil.

How Energy is Used in the U.S. Economy

In 2012, the U.S. consumed 18 % of total world energy, which includes petroleum, natural gas, coal, and electrical generation (EIA 2015).

As you can see in Fig. 5.1, petroleum represented 36 % of all energy used in the United States. Of that petroleum, 71 % was used by transportation, 23 % by industry, 5 % by residences and for commercial uses, and just one percent to generate electric power. This chart also shows that transportation is 93 % dependent on petroleum, though for ships, locomotives, and trucks, it is closer to 99 % since they use little to no ethanol, biodiesel, or natural gas.

The 64 % of remaining U.S. energy use (not fueled by petroleum) goes to generate electric power, heat homes and buildings, the high heat required by industrial processes, and so on.

Fossil fuels—petroleum, natural gas, and coal—provide 82 % of U.S. energy. Since they are finite, it is hard to conceive of a more critical goal for society than figuring out how to best spend our remaining fossil fuels.

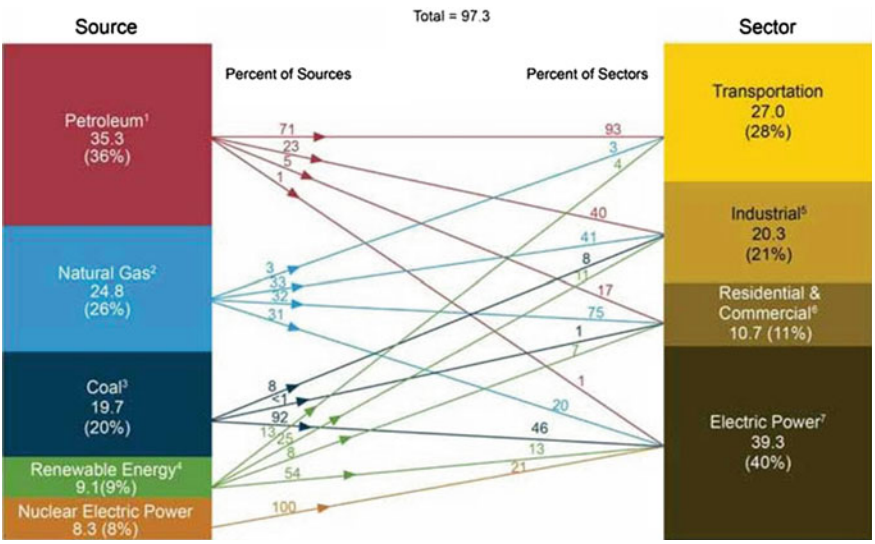

Fig. 5.1 Primary energy consumption by source and sector 2011 (Quadrillion BTU). *Source* EIA (2012)

Energy Return on Investment or EROI

How can we make the best choices about how we spend our remaining energy? Life cycle studies—remember the pencil—can help business analysts find cost-cutting measures. But when it comes to examining the efficiency of an energy source, for instance an energy generating wind turbine and whether or not a better option exists, you need to determine the Energy Returned on (Energy) Invested, the EROI. This is the total energy generated by the wind turbine over its lifetime divided by the energy to build, operate, and recycle it. Its EROI should inform our energy choices.

Clearly fossil fuels have an unquestionably high EROI, because all of our infrastructure and manmade goods were built with fossil energy, and fossil fueled industrial agriculture has dropped the percent of U.S. farming population from 90 to 1 % now (USDA 2012).

When You Do an EROI Analysis, Clearly a Low EROI Is a Problem

There are many investigators that argue that what is important is a positive EROI [e.g. see review by Farrell et al. (2006)]. But it seems clear that to run a modern society you need not just a positive, but a very positive EROI.

Charles Hall, one of the founders of EROI methodology, initially thought an EROI of 3 was enough to run modern civilization, which is like investing $1 and getting $3 back. But after decades of research, Hall concluded an EROI of 12–14 might be necessary to sustain culture and the arts, 12 to provide health care, 9 or 10 for education, 7 or 8 to support a family of workers, 5 to grow food, and so on down to a 1.1 EROI to extract oil, where all you "can do is pump it out of the ground and look at it" (Lambert et al. 2014).

Murphy (2011) found that so much net energy is provided by any energy resource with an EROI of 11 or higher, that the difference between an EROI of 11 and 100 makes little difference. But there is such a large, exponential difference in the net energy provided to society by an EROI of 10 versus 5, that the net energy available to civilization appears to fall off a cliff when EROI dips below 10 (Mearns 2008).

Weissbach et al. (2013) found that it is not economic to build an electricity generating power source with an EROI of less than 7.

There are many problems with EROI studies. They're bound to miss a few steps and exclude energy inputs that are indirect but vital. For example, the Great Pencil Saga left out packaging, distribution, and the final ride to the garbage dump. This can be a problem in EROI studies—when boundaries are too narrow, leaving out steps, operations, and energy inputs such that a misleadingly high EROI is calculated.

Another problem is that EROI research has tended to use national level data rather than site-specific actual data in part because privately owned enterprises tend not to keep track of energy inputs but rather just economic data. Additionally, they tend not to want to share their data with scientists, and when they do, it is in their self-interest to provide only data from their best performing locations.

In my opinion the study that ought to be a role model for EROI standards and methodology is Prieto and Hall's "Spain's Photovoltaic Revolution" (2013), (and also see Murphy and Hall's (2011) protocol for determining the EROI of fuels). The Spanish government saw much good coming from promoting solar power for their sunny environment. Spain imports 90 % of its fossil fuels, more than any other European nation, so it would seem that this would lower expensive oil imports as well. There'd be long-term research and development, a Spanish solar industry, and many high-tech jobs created, since the components for the solar plants would be manufactured locally. To encourage the solar industry, the government provided high subsidies (as much as 64 cents per kWh) to encourage the PV industry.

Prieto and Hall (2013) calculated the EROI of photovoltaics in Spain using a comprehensive approach to energy inputs. Where money is spent they attempted to calculate an energy cost for that money spent. They derived an EROI of 2.45: 1, whereas Raugei et al. (2012) used more narrow boundaries and calculated an EROI nearer to 6–12:1 (unfortunately, a number of issues make it hard to compare the two).

Prieto and Hall used several years of Spanish government data, from over 50,000 large installations at optimal, efficient, multi-megawatt, and well-oriented facilities. Author Prieto actually built some of these Spanish facilities himself, so he understood how to account for every penny. Their study included dozens of parameters not considered in other solar PV studies. The result was a very low EROI of 2.45 in sunny Spain. Even if solar panels were 100 % efficient, the EROI would only go up by a third. And since the Prieto and Hall book was published, Prieto has found additional inputs that would have led to a negative EROI, such as labor energy and the energy to stabilize the electric networks. Not everyone accepts this analysis, but I do think that at a minimum its comprehensive nature is a model for EROI analysis.

Additionally, Spain's photovoltaic revolution, when seen in the clear light of day, was a financial fiasco.

Because the government subsidy was so high, far too many solar PV plants were built quickly—more than the government could afford. This might not have happened if global banks hadn't got involved. They handed out credit like candy.

Even before the financial crash of 2008 the Spanish government began to balk at paying the full subsidies, and after the 2008 crash in Spain (which was partly brought on by this over-investment in solar PV), the government began issuing dozens of decrees lowering the subsidies and the allowable profit margins of the private solar PV sector. In addition, utilities were allowed to raise their electric rates by up to 20 %.

Despite these measures, the government of Spain is still spending about $10.5 billion a year on renewable energy subsidies and on many lawsuits against the lowering of subsidies and profit margins (Parnell 2013a, b). Many solar companies went bankrupt after the financial crash, and about 44,000 of the nation's 57,900 PV installations are almost bankrupt (Nikiforuk 2013). Nor were new jobs, research, and development created, since most of the equipment and solar panels were bought from China.

The end result was a massive transfer of public wealth to private solar PV investors of about $2.33 billion Euros per year. Businesses that depended on cheap electricity threatened to leave Spain.

Conclusion

Replacing oil is a challenge to civilization, and life as we know it. Meanwhile, as long as we have oil, we live in a can-do world. Out of water? Drill a thousand feet deeper or build a desalination plant. Out of fish? Catch the last schools with sonar and spotting planes and then move your efforts to Antarctica. Just wave the magic oil wand, and voila, you can do anything.

But just because it is possible to do anything doesn't mean it should be done. If what we do with the remaining oil is build millions of wind, wave, solar, nuclear, and other energy facilities, then we'd better be damned sure that all the oiliness is accounted for in EROI studies and that we're not wasting the remaining precious oil.

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Chapter 6
Peak Oil and Transportation

Peak oil doesn't mean "running out of oil." There will be lots of oil in the ground indefinitely. Peak oil occurs when oil production begins to inexorably decline, either for a field, a nation, or in the most common use, globally. Clearly, this will happen someday, because oil is finite. Most of the world's largest oil fields were discovered over fifty years ago, and are still the source of 60 % of our oil. In fact, since the 1960s, the world has consumed more oil than what has been discovered, and the average size of new oil fields has declined, leaving us heavily dependent on the original giant oil fields discovered many decades ago. (Aleklett et al. 2012; NRC 2006). Sooner or later, this math dictates supply shortages.

Hallock et al. (2014) gives data that show that peak oil already has occurred for most oil-producing nations, and has or is likely soon to happen for the entire world. There is very little comprehension of this by the public because gasoline prices have been falling, although they are still high by historical standards.

Since the 1970s, the price of oil has repeatedly seesawed up and down, cycling from cheap to nose-bleed high prices, as mismatches have occurred between supply and demand. In 2015, the world has an oil glut, and demand reduction from those so poor that any price is too much to pay, so prices have dropped. These cycles—supply and demand mismatches—most likely will continue. But they do not negate the fact that sooner or later, the amount of oil coming out of the ground will begin to decline.

Anticipating when and how quickly the flow of oil might drop is critical, because commercial transportation is dependent on oil. Like musical chairs, when the flow rate declines, transportation players get removed from the game. What will happen when the music stops?

Consider just the case of trucks. Currently, the nation relies on a fleet of ten million trucks. Phasing over to a non-oil diesel fuel would require modifying this fleet as well as the fuel distribution system that feeds 160,000 service stations. Even if this were technically feasible, how much time, money, and energy would it take do this, or, alternatively, to build an electrified transportation system with millions of miles of overhead wires for trucks and locomotives?

The Four Horsemen of the Apocalypse are not the only threats to civilization as know it. Let's take a sobering look at the risks to the commercial transportation system, where goods from all over the globe ride to us on a flow of abundant, affordable fossil fuels.

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You'd think our supply of fossil fuels was bottomless. And you'd never know peak oil is an issue. Since 2011, U.S. politicians, energy companies, and other experts have boasted that horizontal drilling ("fracking") has led to a century or more of oil and natural gas independence (House 112-176 2012 and 113-1 2013).

Representing this point of view, Congressman Tom Rice of South Carolina, at a House hearing titled "A roadmap for prosperity" on November 18, 2014, said "Eight years ago, when President Bush was in, they were talking about something called peak oil theory, where they said we had already discovered all of the recoverable oil and it was going to get lower and lower, and it was going to be harder and harder to recover and that we were at our finite limits. That shows you how wrong science can be, because in the last five years we have had the largest oil boom in history right here in the United States."

If such optimism is unfounded, the U.S. risks being blind-sided. The Government Accountability Office warned in 2007 that coping with a peak in oil production depends on our preparedness, and would be most dire if a peak occurred soon, without warning, and was followed by a sharp decline, because alternative energy sources for transportation are not yet available in large quantities. Such a peak would cause a worldwide recession and severe economic damage. The U.S. consumes the most oil, and is the most dependent country on oil for transportation, and so perhaps the most vulnerable of all industrialized nations (GAO 2007).

Former U.S. Senator Joe Lieberman noted oil shocks could also happen with just one well-orchestrated terrorist attack or political upheaval causing an overnight price spike that would send the global economy tumbling and the industrialized world scrambling to secure supplies from a limited number of oil producers. Wars have started over such competition.

Said Lieberman, "China is moving aggressively to compete for the world's limited supplies of oil not just with its growing economic power, but with its growing military and diplomatic power as well. We depend for our oil on a global gallery of nations that are politically unstable, unreliable, or just plain hostile to us. All that and much more should make us worry because if we don't change—it is within their borders and under their earth and waters that our economic and national security lies. Doing nothing about our oil dependency will make us a pitiful giant—like Gulliver in Lilliput—tied down by smaller nations and subject to their whims. And we will have given them the ropes and helped them tie the knots. I fear that we are literally watching the slow but steady erosion of America's economic and military power and our political independence."

Decrying the nation's absolute dependence on oil to fuel our cars and trucks, Lieberman said, "We need to transform our total transportation infrastructure from the refinery to the tailpipe and each step in between because transportation is the key to energy independence" (Senate 109-412 2006).

In 2006, the National Research Council (NRC) conducted a workshop on Peak Oil, and explored how to bring the issue to the attention of politicians and policy makers before a crisis began. The NRC workshop concluded the obvious, that a long lead time was required to increase oil supplies, transition to oil substitutes, and reduce oil demand. If peaking happened sooner than expected, critical decisions on how to invest limited capital would need to be made, and little confidence was voiced at the workshop over whether a crash program would work, since the oil and gas industry might not have the infrastructure or skilled and experienced technical people to undertake such a program (NRC 2006).

Risks and Risk Management

Well-run businesses identify worst-case risks and have mitigation plans for them. Does the nation have a plan to keep freight and farm equipment moving come the day that oil supplies decline? The Department of Energy commissioned such a study in 2005. This report recommended preparing at least 10–20 years ahead of peak oil production because it is both expensive and requires decades to develop and produce increasing amounts of oil from the remaining poor quality oil such as Canadian oil sands, Venezuelan heavy oil, ultra-deep sea oil, and liquefied coal (Hirsch 2005).

In 2013, Robert McNally, President of the Rapidan Group, told the House of Representatives that energy transitions take decades, if not generations, especially from oil, which is far superior to biomass or renewables due to energy density, high concentration, abundance, and ease of transport and storage. A transition cannot be done in a "multiyear moon-shot. Pretending otherwise misleads citizens and distracts from serious debate about real circumstances and practical solutions" (House 113-2 2013).

Peak Oil May Be Less Than 20 Years Away

In fact, peak oil may have already happened in 2005 or 2006, despite high oil prices. Crude oil and condensate production have been on a plateau since then (Aleklett et al. 2012; Kerr 2011; Murray 2012; Newby 2011; IEA 2010; Zittel et al. 2013).

Table 6.1 contains global oil production that can be used for diesel trucks, locomotives, and ships. Ethanol is not included because it harms diesel engines. Natural gas liquids (NGL) are left out because most are used to make plastics and other products. Only one-third can be blended into transport fuels and NGLs have one-third less energy than crude oil per unit volume.

Table 6.1 World production of crude oil and lease condensate 1000 b/d

2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
73,866	73,478	73,164	74,062	72,871	74,653	74,734	76,160	76,248	77,833

Source EIA. 2015. International Energy Statistics. Petroleum. U.S. Energy Information Administration.

Although oil production in 2014 was 5.4 % higher than 2005, this slight increase may only be temporary. North America is responsible for over half of this increase due to tight oil production, which is likely to peak by 2020 (DOE/EIA 2015 low/ref cases; Hughes 2014). Tight oil is obtained by hydraulic fracturing ("fracking") and horizontal drilling, and is also called shale oil or "fracked" oil. It exists in a limited area, and, not surprisingly, the best "sweet" spots were drilled first. Remaining areas are not likely to be as productive, on average.

Tight oil may peak even sooner, since two-thirds of the nation's reserves were thought to reside in California's Monterey shale, but in May 2014, it was discovered that only 4 % appear to be recoverable (Sahagun 2014). The decline rate of tight oil is so high, that if new drilling stopped, production would fall 40–45 % per year (Hughes 2014).

Oil Field Decline Rates

Of the roughly 47,500 oil fields in the world, 507 of them, about one percent, are giant oil fields holding nearly two-thirds of all the oil that has ever been, or ever will be produced, with the largest 100 giants, the "elephants," providing nearly half of all oil today (Aleklett et al. 2012).

Since giant oil fields dominate oil production, the rate they decline at is a good predictor of future world oil production. In 2005, they provided 60 % of world oil.

Giant fields only begin to decline after a long plateau phase where production fluctuates within a 4 % range. In 2007, the 261 giants past their plateau phase were declining at an average rate of 6 % a year. Their decline rate will continue to increase by 0.15 % a year, to 6.15, 6.3, 6.45 % and so on. By 2030 these giants, and the other giants joining them as time goes on, will be declining at an average rate of over 9 % a year (Hook 2009; IEA 2010).

Production doesn't drop to zero, but eventually flattens out with a long tail of oil production, but at a very low level. Since nongiant oil fields decline at much higher rates, especially offshore and tight oil, by 2030, the average decline rate of all oil fields past their peak production will be higher than 9 percent.

This means that by 2030, from half to two-thirds of global crude oil production will need to be replaced—40 to 50 Mb/d of today's 77.8 Mb/d (Hook 2009; IEA 2008; 2013). Making up this shortfall will be difficult, since four out of five barrels now come from fields found before 1973 and the majority of them are declining.

Although new enhanced oil recovery (EOR) techniques not yet invented are touted as a way to wring more oil out of the ground, it is risky to assume that whatever advances in oil drilling are needed to produce abundant supplies of cheap oil at their current rate will happen. To do so is a matter of faith, not science (Davies 2000).

So far, EOR in giant fields has had the *opposite* effect, *increasing* the decline rate after peak production (Hook 2009), because oil extracted now is unavailable after the peak, making the decline rate steeper. For example, Cantarell in Mexico, the second largest oil field ever found, declined at 20 % rates due to the EOR used to increase the maximum rate of production (Murphy et al. 2011).

Where Will Additional Oil Come From?

The Arctic, the area north of the Arctic Circle, that many feel should be off limits to drilling, has about a quarter of the remaining undiscovered oil and gas resources globally. About 70 percent is expected to be natural gas, the remainder oil. Perhaps a quarter is onshore, with the rest offshore. The U.S. Arctic may have 35 billion barrels of oil, equal to 5 years of U.S. consumption. So far, drilling in this harsh environment has not gone well. Royal Dutch Shell almost lost a drill ship off Kodiak Island in 2012. In September, 2015, Shell announced that after spending $7 billion, it was ending its Arctic effort without ever producing a single drop of oil.

If drilling proceeds in the Arctic, it will take decades to begin to produce oil, and it will be very expensive. Infrastructure will have to be built. Arctic oil can't be produced without ports, airfields, roads, rail, communication networks, and fuel and electricity delivery systems. An oil field can only be found by drilling in short, 1-to-4-month ice-free summers. If open water lasts 3 months or more, there is time to drill an exploration well; otherwise, it can take multiple summers to complete a single well. Then more drilling is needed to determine the size and scope of the oil field. Oil production can only begin when a field large enough to justify the high investment is found, and is possible only with new technology that hasn't been invented yet (NPC 2015). Arctic oil will require supply chains stretching over long distances that pose great risk to arctic ecology (Patzek 2012).

Meanwhile, the Alaskan pipeline could turn into an 800 mile-long popsicle. Corrosion, or a 9-day power outage in the winter, or throughput declining to less than 400,000 barrels a day (likely by 2020)—any one of these scenarios would cause the crude to cool down so much that it becomes too thick for pumps to push it through (Waldman 2015).

Canadian oil sands also contributed to the 5.4 % increase in oil production since 2005, increasing from 0.974 to 2.1 Mb/d in 2014 (2.7 % of world oil production). There are about 170 billion barrels thought to be recoverable, equal to 6 years of world oil consumption. In a crash program to ramp up production as quickly as possible, production would likely peak in 2040 at 5–5.8 Mb/d (NEB 2013; Soderbergh et al. 2007).

Reaching 5 Mb/d will get increasingly (energy) expensive, and difficult to attain if an EROI of 7–14 turns out to be what is required, as mentioned in Chap. 5. Mined oil sands have the highest EROI of 5.5–6, while in situ EROI is only 3.5–4 (Brandt 2013).

Already, oil sand production forecasts for 2030 have declined 24 % over the past 3 years, from 5.2 Mb/d in 2013, to 4.8 Mb/d in 2014, to 3.95 Mb/d in June 2015 (CAPP 2015).

There are between 380–652 billion barrels (13–22 years of world consumption) of Venezuelan heavy oil, but like Canadian oil sands, it might also take decades to increase production from 0.4 Mb/d now to 5 Mb/d in the future.

Finally, the one trillion barrels of "oil" in Colorado's kerogen-rich formations is not commercial. Left alone for millions of years it might be, but no oil is produced now despite 35 years and billions of dollars spent trying by Shell, Chevron, and Exxon. The EROI is a low 1 to 2 since it has to be cooked at high temperatures for a long time, using a lot of energy. Nor is there enough water in this tiny area of Colorado to produce a meaningful number of barrels a day (Udall 2005; Cleveland et al. 2010).

Other Threats to Oil Supplies for the Transportation System

Economic issues. Whenever oil prices become high, the financial system falls into an "oil trap." High oil prices have helped trigger 11 out of 12 past recessions since World War II (Hamilton 2013). Recessions drive oil prices down, slowing or stopping new oil projects, possibly for a long time, since for unemployed and low wage earners, oil at any price is barely affordable. In a recession, credit shrinks and it is hard to find the capital to drill for more oil or transition to alternatives.

The oil trap might also snap if investors generally became aware of peak oil, because this could cause a financial panic, crashing stock markets, and capital might not be available to lend to oil projects (Macalister 2009). A 2010 German military peak oil study also thought peak oil awareness was likely to lead to market collapse, and that the decline of oil would eventually cause global economic failure, because in a shrinking economy, companies could not make and distribute profits, or pay back debts. As businesses and nations went bankrupt, supply chains would break (BTC 2010).

Many oil-producing countries are not investing enough in their oil fields, and lack technical expertise, which can harm oil fields and reduce the ultimate amount of oil produced (GAO 2007).

Exports from oil-producing countries may decline due to increasing domestic use, or to make oil resources last longer for future generations. This would bring the onset of oil decline sooner (Hirsch 2008).

China and India have increased their oil imports every year and are able to outbid other nations for exported oil. If their oil imports continue to grow as they have so far, theoretically China and India would be buying all exported oil in 2030 (Brown 2013).

If the U.S. is outbid by other nations on declining oil exports, perhaps America could trade food for oil, though most oil producers are already food secure since they have bought millions of acres of crop land in Africa, South America, and other nations to feed their populations (Pearce 2012).

Table 6.2 Chokepoints vulnerable to war, terrorism, and other disruptions

2011 World oil transit chokepoint	Million barrels per day (MB/d)	% of 2011 World oil production (76.25 Mb/d)
Strait of Hormuz	15.5	20.3
Strait of Malacca	13.6	17.8
Bab al-Mandab	3.2	4.2
Bosporus Straits	2.9	3.8
Suez Canal	1.8	2.7
Sumed Pipeline	1.1	1.4
Panama Canal	0.8	1

Source EIA (data estimates based on APEX tanker data) from (House 112-4 2011)

Political risk. According to the IHS Global Risk Service, two-thirds of the world's remaining oil is produced by countries with medium-to-high levels of political risk.

Over half of world oil production moves through oil chokepoints where supertankers are vulnerable to attack (Table 6.2).

Wars, strikes, terrorism, or attacks on supertankers, refineries, and oil chokepoints would result in disruptions regardless of remaining oil reserves in the ground.

John Hofmeister, former president of Shell Oil, said oil prices might triple if the Straits of Hormuz were blocked (House 112-4 2011).

Conclusion

Clearly oil is finite. Clearly, commercial transportation is vulnerable. The sooner the onset of oil decline, the more we're locked into existing transportation and fuel distribution infrastructure, and the less fossil energy, time, and capital there is transition to the elusive "Something Else."

And then the frantic race will be on to get the most bang for our BTU buck in the dwindling piggy bank of whatever fuels are available. I'll discuss that future in the following chapters.

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Chapter 7
Distributing Drop-in Fuels: The Fastest Road to Something Else

It is almost impossible to exaggerate the importance of our transportation system. Take a deep breath and think about this: the United States is locked-into \$1.11 trillion dollars of transportation vehicles supported by \$4.62 trillion of transportation infrastructure comprising 12 % of all the wealth in the nation (U.S. Commerce 2012).

Ships, locomotives, and trucks with diesel engines can last up to 40 years and travel a million miles. It would take decades to replace them. Therefore, the best alternative fuel is one that doesn't require getting rid of them—a "drop-in" fuel. Otherwise, we face the chicken-or-egg problem of no one buying a new-fuel vehicle because of a lack of stations that sell the new fuel, so not many alternative vehicles are made, and service stations won't add the new fuel if there aren't enough customers (GAO 2011).

A drop-in fuel would be able to use the nation's incredibly cheap and energy efficient 190,000 mile oil pipeline system, which distributes oil to 1350 distribution terminals for delivery to 160,000 service stations. Interstate petroleum pipelines transport 31 million barrels (1.3 billion gallons) of crude and refined oil every day (NACS 2013). It would take 39,500 rail cars or 162,500 trucks to move this amount of oil daily.

Pipelines are by far the cheapest way to move oil at 1.5–2.5 cents per gallon per thousand miles. Rail is five times more expensive at 7.5–12.5 cents, and trucks about 20 times more, 30–40 cents (Curley 2008).

Unfortunately, ethanol and biodiesel (which aren't drop-in fuels), can't travel in oil pipelines because:

1. Designing pipelines that could carry either oil or biofuels requires overcoming another obstacle: Oil leaves behind some water and impurities. Both ethanol and biodiesel are good solvents, and would pick up and mix with this water and impurities, and these contaminants could destroy engines.
2. Biodiesel can contaminate oil with methyl esters, making jet fuel unsafe (APEC 2011).

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3. Ethanol corrodes and cracks steel, damages seals, and lets water into oil pipelines. For that reason, the existing 190,000 mile oil pipeline network is off limits to ethanol. Few ethanol pipelines exist because they cost $4 million per mile (GAO 2011; Melaina 2013).
4. Oil can travel only one-way, which is mainly from coastal refineries inland, yet most biofuels move from the Midwest outward.

Instead of being moved by cheap and efficient pipelines, ethanol travels on trains, trucks, and barges. Diesel, twice as energy dense as ethanol, is used by locomotives to haul 60 to 70 % of ethanol in 304,000 30,000-gallon tank cars (1 % of all carloads) traveling 34.3 billion ton-miles (AAR 2015). Half a million trucks haul 29 % and the remaining 5 % goes by barge every year.

Hydrogen is not a drop-in fuel—it can't be burned by existing engines—and can't travel in oil (or natural gas) pipelines because it requires special steel that won't become brittle and crack or fissure.

Natural gas is not a drop-in fuel, though natural gas can be delivered by natural gas pipelines to service stations and turned into compressed natural gas (CNG) to power trucks set up with special tanks and engines. Liquefied natural gas (LNG) needs to be delivered by truck. Methanol or dimethyl ether made from natural gas requires too many fueling and vehicle infrastructure investments.

Next Stop: Service Stations

A new LNG station can cost up to $2 million, and there are only 73 public and 38 private LNG stations in the U.S. A new CNG station costs up to $1 million. About half the 1500 CNG U.S. stations service private fleets of buses, garbage trucks, and delivery vans.

Adding E15 (15 % ethanol, 85 % gasoline), E85, or biodiesel can cost $100,000–$200,000 (underground tanks and pumps need to be replaced), too much for mostly Mom and Pop operations, where more profits are made from junk food than fuel.

This is why E15, biodiesel, hydrogen, CNG, and LNG are sold at less than 1 % of service stations and E85 at less than 3 % of them.

Nearly all heavy-duty vehicles have diesel engines, which are very fussy, and can only burn #2 diesel which is made to very exact specifications. They can't burn gasoline, nor diesohol (diesel and ethanol), and only a small amount of biodiesel, since heavy-duty diesel engine warranties typically allow B5–B20 biodiesel at most, and biodiesel is often avoided entirely because it can shorten engine life (Borgman 2007), and gets less mileage.

Ships and aircraft are reluctant to use biodiesel, or any non-drop-in fuel, because it's dangerous and potentially fatal if their engines fail. Railroads don't want to risk stranding a locomotive, since few spare locomotives exist (Voegele 2011).

Cost to Create Drop-in Fuel

Even if a drop-in fuel can be created, it may be too expensive. Many energy-intensive steps are needed to turn biomass, oil sands, coal, and natural gas into drop-in fuels due to their chemical and physical properties being so different from crude oil in viscosity, lubricity, water content, flashpoint, cetane number, carbon chain length, ash content, cloud point, and other factors.

Natural gas is not a drop-in fuel, but can be converted to one in a Gas-to-Liquid (GTL) plant. These are built near locales with decades of cheap gas (NRC 2009). The $19 billion GTL plant in Qatar only produces 140,000 barrels/day with profits mainly from high-value chemicals, not fuel.

Railroads Can't Afford to Replace Their Locomotives

As an efficient mover of freight, rail has a lot of advantages going for it. It also has an invisible disadvantage.

Trucks, airlines, and barges use highways, airways, and waterways mostly paid for by taxes and the government. Roads get 62 %, airports 13 %, and water transport 5 % of federal government transportation money. Railroads get nothing.

Railroads are privately owned and spend more capital than nearly all other businesses to maintain what they have, yet are less profitable than the average enterprise. Locomotives burn diesel and only diesel. A non-drop-in fuel would require spending $50 billion to replace 25,000 locomotives worth $2 million each, and billions more for a new distribution system. Railroads are already spending over $12 billion dollars to comply with the Rail Safety Improvement Act and meet EPA Tier 4 emissions standards. Additionally, there's a risk that freight would shift to trucks due to time lost swapping locomotives, refueling more often, and having to charge higher rates.

Conclusion: Time Is Running Out

Finding alternative liquid fuels for military transportation will be even harder than for trucks, rail, and shipping. The U.S. Navy uses 187 types of diesel engines, 30 kinds of gas/steam turbine engines, 7,125 different motors, several types of nuclear reactors in aircraft carriers and submarines, and turbojet, turboprop, turboshaft, and turbofan engines in aircraft. Each of them needs just the right combination of energy content in both mass and volume (CNA 2009).

In an oil shock, trucks, rail, and ships need to be able to run on something else, and post fossil fuels the "something else" needs to be renewable. The next chapters look at fuel options that are already commercial or might be available within 10 years.

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Chapter 8
Post Fossil Fuels, If Biomass Is the "Answer to Everything," Is There Enough?

Biomass such as wood and crops will need to replace natural gas, coal, and oil someday. It is the "Answer to Everything," a feedstock providing:

1. transportation fuel
2. the source of the half-million products now made with fossil fuels
3. baseload electricity and balance for intermittent power
4. high-temperature heat needed to make cement, steel, ceramics, and glass
5. heat for homes and businesses

A lot of biomass is already spoken for. It provides food, grazing, and heats 10 % of American homes. Even the so-called "crop waste" is increasingly tilled-in by farmers to replace fertilizer and improve soil health.

Is there enough biomass for it to be the answer to everything? Certainly, besides air, dirt, and water, plants are the most abundant and renewable resource that could possibly scale up enough to replace fossil fuels.

Few studies consider how biomass would be shared among all these competing uses.

California found that at best, due to limited irrigation water, California has the biomass to make 18 % of transportation fuel, but that a quarter of this biomass should be allocated to utilities to generate electricity (Youngs and Somerville 2013).

All things considered, biomass ought to be converted to #2 diesel to keep trucks and trains running. Instead, 40 % of the corn crop is wasted on ethanol. Not only is the EROI on ethanol extremely low or even negative, but ethanol can't be mixed with diesel to make diesohol, otherwise engines misfire, won't start when they are cold, and pistons are tarnished.

Biodiesel is just 1 % of total diesel production by volume, with soybeans making up 57 % of that feedstock. Soybean production is heavily dependent on incentives and tax credits (NRC 2014b). When the $1 per gallon biodiesel blending credit expired in 2010, production of soy-based biodiesel fell 42 %. Soybeans require a great deal of fossil inputs (fertilizer, pesticides, and tractors). The use of unsustainable palm oil to make biodiesel has destroyed rainforests, diminished biodiversity, and increased CO_2 emissions in Indonesia to the world's third highest levels.

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Oil is also a biofuel. Alas, it is nonrenewable, since it took Mother Nature millions of years to brew, rendering 196,000 pounds of plants into one single gallon of oil. That is equivalent to cramming 40 acres of wheat into your gas tank every 20 miles. Every year, the fossil fuels burned globally are equal to 400 times the planet's total annual plant growth, including the microscopic plants in the ocean (Dukes 2003).

And therein lies the rub. We're trying to make biofuels like ethanol from plants faster than tens of millions of years. And in many steps with more "oiliness" than a pencil (see Chap. 5), from the planting of seeds, to fertilizer application, pesticide spraying, harvest, tractor haul to farm storage area for pulverization and bale wrapping, truck haul to the biorefinery, unloaded, ground up, conveyer belt to liquefier, heated, saccharified, fermented, evaporated, centrifuged, distilled, scrubbed, dried, wastewater treated, and delivered to customers by diesel-fueled rail or truck, since ethanol can't travel by far cheaper pipelines. Liquid energy from the sun—not so simple.

Not surprisingly, all these steps to make ethanol take so much fossil fuel energy that the net energy (EROI) provided to society is close to break-even or negative (Farrell et al. 2006; Hammerschlag 2006; Murphy et al. 2011; Pimentel et al. 2005). Not everyone agrees with that. Higher EROI results can be found in research paid for by industry (i.e., the National Corn Growers Association) in non-peer-reviewed journals using very narrow boundaries.

Rather than argue over ethanol EROI, let's move on to other biomass limits.

Like corn, algae can be used to produce ethanol. But the number of steps involved exceeds that of corn. Photobioreactors are still in the development stage as far as fuel production goes, so open ponds of algae are the only option at this point. The National Research Council (NRC 2012) concluded that the scale-up of algal biofuel production to replace even 5 % of U.S. transportation fuel would place unsustainable demands on energy, water, and nutrients. The Department of Energy (DOE 2010) found that the quantity of water required to grow algae for biofuels could "approach the same order of magnitude as large-scale agriculture" and easily become a "show-stopper." Algae are hungry critters and need as much nitrogen from commercial fertilizer as large-scale commercial agriculture does. To supply 5 % of U.S. transportation fuel, algae would require as much as 44–107 % of total nitrogen fertilizer use in the United States, and would also require 20–51 % of *total* phosphorus as well (Pate 2004). Algae are also tasty critters, and protozoans that invade a pond can eat them all up within 12–18 hours. Ponds are also invaded by other, less desirable algae species and predators such as bacteria, fungi, and insects. (This doesn't begin to cover the issues with algal biofuels—see my article *Dozens of reasons why the world doesn't run on algal biofuels* at http://energyskeptic.com/2015/algae/).

There's a risk of turning a renewable fuel non-renewable if too much is harvested for all societal needs. For example, if you yanked every plant in America out of the ground, roots and all, and burned them to create energy, you'd get 94 exajoules (EJ), less than the 105 EJ of fossil fuels Americans use per year (Patzek 2005). To cope with our new barren landscape, we could all pretend we lived on Mars for several years.

Europe uses 150 EJ/year, equal to 200 billion cubic meters (bcm) of biomass, orders of magnitude more than the annual 2.8 bcm crops harvested there, or the 6.2 bcm of coal and 5.7 bcm of oil transported and consumed every year (Richard 2010).

If photosynthesis were more efficient, more renewable biomass could be produced. But on average, only half a percent of sunshine is turned into plant biomass (NRC 2014a).

Plant biomass must survive assaults by pests, disease, drought, and floods before harvest. Of the energy potential in biomass, one quarter of that energy is lost during harvest and baling (Ruth 2013), and 15 % more is lost in storage (NPC 2012). You need land to grow biomass, and cropland is dwindling away, gone to development. The United States lost over 59 million acres of cropland between 1982 and 2010 (NCRS 2013). At that rate, which cannot continue, it would all be gone in 170 years. Talk about eating your seedcrop!

Climate change poses a major threat to a biomass-powered world. Heat and extremes in rainfall and drought would reduce biomass production and degrade soil, increasing erosion. Plants will be stressed by more ground-level ozone. Heat increases weeds, pests, disease, and invasive species. Heat also reduces forage grass quality, while increasing the number and severity of wildfires (Hatfield 2014).

Current industrial farming practices have accelerated erosion of topsoil to 10–40 times faster than it's geologically replenished, and the land takes several hundred years or more to recover. Iowa, the heart of America's Corn Belt, has some of the best topsoil in the world. So much Iowa soil has been "mined" to grow crops that, on average, the topsoil has diminished from 18 to 9 inches in depth in less than a century (Pate 2004, Klee 1991). Productivity drops off sharply when topsoil reaches 6 inches or less. Historically, it takes most civilizations 1500 years to exhaust their soils. Then they collapse (Montgomery 2007).

Cellulosic ethanol plants offer hope for the future of biomass, but we remain far from the Promised Lands. Cellulosic plants are still not commercial (Rapier 2015), and we don't know yet if it is possible to make positive net energy cellulosic biofuels. It is hard to do because plants evolved lignocellulose 300 million years ago to keep creatures from eating them, and we are still trying to learn how to break down and transform this material into fuel. So far, only fungi and bacteria can do this, which is why animals and termites outsourced cellulose breakdown to many kinds of bacteria in their guts, where the toxic secretions of one are a 5-star meal for another. Unfortunately, none of their secretions are diesel #2. Cellulosic biorefineries have yet to genetically engineer diesel-pooping creatures.

Waste not, want not are words to live by. But if the plan is to run ten million trucks on waste oil from fast food joints, then the only question is—can we eat enough french fries? Biodiesel, which provides only 1 % of diesel fuel today, needs to scale up exponentially. The french fry strategy could pay off. Our nation of french fry eaters would need to lose weight, and we could have them workout on treadmills to generate electricity.

If biomass is the "Answer to Everything," is there enough? Clearly not. It would be a Pyrrhic victory to deplete topsoil and aquifers, and mow down (rain)forests to enable biofuel transportation.

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There are many more problems with biofuels that I cover in:

- *Peak Soil: Why Biofuels are Not Sustainable and a Threat to America's National Security* at http://energyskeptic.com/2015/peaksoil/.
- *Analyzing energy breakthroughs: a skeptical look at kelp and seaweed fuels* at http://energyskeptic.com/2012/kelp-seaweed-fuel/.

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Chapter 9
Hydrogen, the Homeopathic Energy Crisis Remedy

Homeopathy involves diluting substances so much that there's virtually nothing left of it. Hydrogen is also an empty remedy, so absurd that I wasn't going to waste words and energy on it. But hydrogen is so often mentioned as a solution for the energy crisis that I'm going to attempt to thrust a stake into its heart.

Since water is one of the few substances besides air and dirt abundant enough to scale up as a fuel, hydrogen does seem to be a logical candidate.

But hydrogen gas (H_2) isn't an energy source—it is an energy carrier, like a battery. You have to put energy in to get energy out, and producing H_2 puts you in negative energy territory immediately. To put hydrogen in your tank first requires repeated infusions of energy:

1. To split hydrogen out of water takes a tremendous amount of energy. That is why 96 % of H_2 is made from natural gas, the other 4 % from water that needs to be extremely pure.
2. Once you have hydrogen gas, it must be compressed, or purified for fuel cells, or liquefied and chilled to −423 °F using energy-demanding cryogenic support systems.
3. Storage tanks and pipelines are heavy and energy-intensive because hydrogen is the Houdini of elements, the smallest one, enabling it to escape through the tiniest imperfections. Consequently, fuel cell engines and storage tanks have many seals, gaskets, and valves. Hydrogen requires expensive, heavy, large tanks, and pipelines made of special steel that won't become brittle and crack or fissure.
4. Hydrogen gas is very flammable and explosive. Remember the Hindenburg?
5. Absent hydrogen pipelines, delivery requires a $250,000 canister truck weighing 40,000 kg delivering a paltry 400 kg of fuel, enough for 60 cars. The same truck can carry 10,000 gallons of gas, enough to fill 800 cars. The hydrogen delivery truck will eat a lot of energy itself: over a distance of 150 miles, it will burn the equivalent of 20 % of the usable energy in the hydrogen it is delivering.
6. Turning that hydrogen back into electricity with a fuel cell will only be 24.7 % efficient. There are multiple stages where energy is lost due to inefficiencies at

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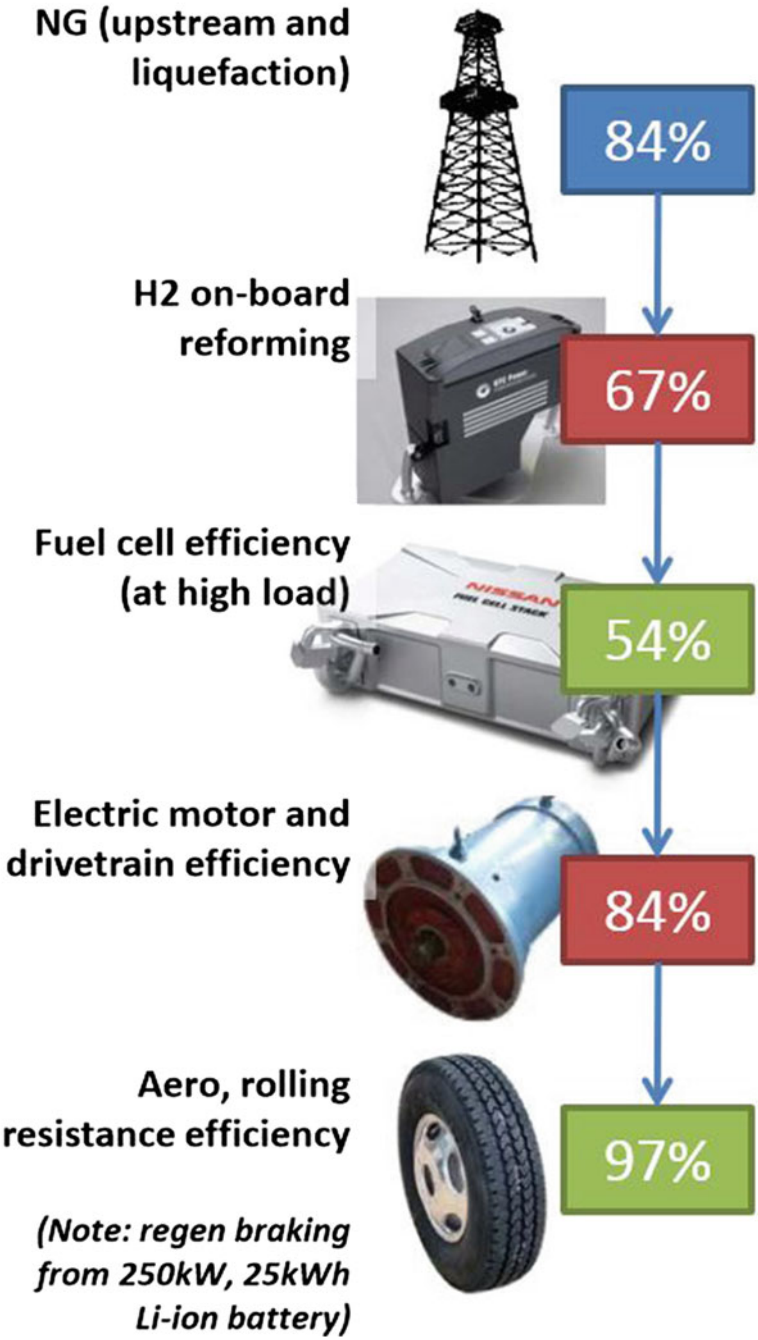

Fig. 9.1 Heavy truck: PEM hydrogen fuel cell on-board reforming. U.S. Department of Energy Vehicle Technologies Program, Estimated for 2020. *Source* (DOE 2011)

each step: Natural gas upstream and liquefaction, hydrogen on-board reforming, fuel cell efficiency, electric motor and drivetrain losses, and aerodynamic/rolling resistance (Fig. 9.1).

7. References and additional information can be found at The Hydrogen Economy. Savior of Humanity or an Economic Black Hole? http://energyskeptic.com/2011/hydrogen/.

Without unlimited energy from fusion, hydrogen is impossible because it requires enormous amounts of energy to make hydrogen gas.

Even if Thomas Edison was resurrected and (in a second miracle) invented a black box that could turn water into hydrogen, it wouldn't be easy to sell cheap hydrogen to a trucker. Trucks don't use hydrogen tanks because they take up 10 % of payload weight (DOE 2011), or fuel cells, because the best only last 2500 h but need to keep on going at least 14,560 h in long-haul trucks and 10,400 in distribution trucks (den Boer 2013).

There is plenty more to be said that would burst the bubble of the hydrogen economy, but this is enough wasted ink.

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Chapter 10
Natural Gas—A Bridge Fuel to Where Exactly?

Natural gas is touted as a "bridge fuel" to "Something Else." But is finite natural gas a long enough bridge to replace diesel and get us to the other side, where the always fetching "Something Else" awaits?

The EIA estimates that there are 6972 trillion cubic feet (tcf) of natural gas reserves world-wide. That would last 57 years at current world-wide consumption rates of 121,283 billion cubic feet per year. There is probably a great deal more to be discovered. Estimates of ultimately recoverable global resources (URR) range from 13,000 tcf to 26,000 tcf, with peak global natural gas ranging from 2018 to 2049 (Coyne 2015). Not all of it will be exploitable, since some will be too far away to get to markets. And not all natural gas is created equal. About 20–40 % of reserves are low EROI "sour" corrosive natural gas containing toxic hydrogen sulfide or carbon dioxide gas, which are (energy) expensive to produce.

The U.S. has 422 tcf, 6 % of world natural gas reserves, with 16 years left at current U.S. consumption rates of 26 tcf. There are another 1844 of unproved resources which would provide 71 years at current consumption rates, if it could all be produced.

But that may be optimistic, because U.S. shale "fracked" natural gas was drilled in the best "sweet" spots first, and remaining areas may not be as productive. As it is, shale gas wells deplete so quickly that up to half of present production needs to be replaced with $42 billion of drilling every year to keep production flat, more than the $33 billion in revenues from fracked natural gas in 2012 (Heinberg 2013). Several geologists predict a U.S. shale gas peak by 2020 (Berman et al. 2015; Hughes 2014; Inman 2014; Powers 2013).

Economic Peak Natural Gas and Tight Oil?

If shale natural gas and oil don't peak geologically, they may peak economically. In the first quarter of 2015, natural gas and oil shale drillers' debt ballooned to $235 billion even when oil was $100 a barrel (Loder 2015a, b). If the shale debt bubble pops, peak shale natural gas and oil could hit before 2020.

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According to the New York Times, shale gas production may not be as cheap or easy as companies say. Data analysis from thousands of wells and communications between geologists, energy executives, and industry lawyers suggest that companies may be overstating production and reserves, reported the Times. An analyst from PNC Wealth Management wrote that "money is pouring in" from investors even though shale gas is "inherently unprofitable." Like the recent credit bubble, the gas boom was fed by tens of billions of dollars in creative Wall Street financing schemes (Krauss 2012; Urbina 2011).

In other words, if shale gas and oil drilling is being funded by financial shenanigans like the mortgage bubble, then some percent of production may be coming from uneconomic resources, which can be produced only so long as Wall Street can sell junk bonds to keep the drilling going.

Whenever natural gas peak occurs, it would be followed by a rapid decline, because U.S. shale "fracked" natural gas provides half of our supplies, with a depletion rate up to 82 % in the first three years. The other half, U.S. *conventional* natural gas, peaked in 1973, and is declining at a rate of 5 % a year.

Import Liquid Natural Gas?

In 2004, when natural gas shortages loomed in the U.S., there was a scramble to build dozens of liquid natural gas (LNG) import terminals. Daniel Yergin said that "In the next five years, [the U.S.] is likely to become a large gas importer; within ten years, it will overtake Japan as the world's largest gas importer… Gas prices have doubled since the second half of the 1990s, placing a new burden on the economy and portending a shortage. Federal Reserve Chairman Alan Greenspan warned recently that dwindling domestic supplies were 'a very serious problem' and a major threat to the U.S. economy and spoke out forcefully on the need to develop LNG supplies" (Yergin et al. 2003). Yergin was not exactly sage in terms of his timing. Time will tell whether he was equally offbase in his advocacy of LNG import terminals.

Back then there was strong opposition to LNG terminals because they were seen as hazardous and a potential terrorist target.

Natural gas is mainly a local resource, with 90 % traveling cheaply in pipelines. This is because the infrastructure to move LNG by ships costs billions of dollars for export terminals where gas is liquefied to −260 °F, and reheated at import terminals to turn LNG back into gas, delivered by specialized ships that boil off up to 0.15 % of the LNG every day of the voyage while also consuming the LNG cargo for propulsion.

It may not be prudent to import LNG. Amory Lovins pointed out that it raises "concerns about security, dependence, site vulnerability, and cost….Iran and Russia [are unlikely to be] more reliable, long-run sources of gas than Persian Gulf states are today of oil" (Senate 109-412 2006).

Or Export LNG? America's Newfound Energy Independence

Congress has been assured that America has 95–300 years of natural gas supplies, enough to export to other countries (House 113-1 2013; Senate 113-1 2013; Senate 113-355 2014).

DOE/EIA (2015) charts don't look that far into the future, but show natural gas increasing from today's 24.3 tcf to between 31.9 and 50.6 tcf in 2040, with no sign of a peak. Not everyone agrees. Geoscientist David Hughes is the author of the most comprehensive publicly available analysis to date of the prospects for shale gas and tight oil in the United States. The DOE/EIA baseline (reference case) projection for cumulative production to 2040 is 50 % higher than Hughes's most likely case, and production rate 170 % higher. These optimistic DOE/EIA projections can only happen if production ramps up enormously, despite the most promising wells having already been drilled. It requires new technologies, new areas drilled, and more money despite the enormous debt (Hughes 2014; Inman 2014; Tinker 2014).

Uncle Sam and big business have bet on energy independence and placed a big stack of chips on the natural gas square of the roulette table. Corporations are building 100 major manufacturing projects totaling $95 billion to take advantage of cheap U.S. natural gas, and utilities plan to replace retiring coal and nuclear plants with gas.

Is There Enough Natural Gas for Transportation?

Currently, natural gas provides 0.1 % of vehicle fuel. Natural gas already has many important uses

- 30.4 % is used for electricity generation. Even more will be used in the future. Hundreds of natural gas power plants are under construction or planned to replace retiring coal and nuclear power plants. Natural gas also plays a key role of keeping the grid in balance as variable wind and solar ramp up and down.
- 28.5 % is used by industry to make industrial products requiring high temperatures such as plastic, epoxy, cement, steel, and thousands of other petrochemicals. Natural gas is also used to make fertilizer from ammonia, which has increased crop production up to five-fold. These fertilizers make it possible for an additional four to five billion people to be alive today. About 3 to 5 % of world natural gas production is used to make 500 million tons of fertilizer.
- 19 % is used residentially (i.e., heat, air-conditioning, cooking, heating water).
- 13 % is used commercially (i.e., retail stores, hotels, restaurants, and other nonmanufacturing activities).

- 5.8 % is used for drilling and production of natural gas and in natural gas processing plants.
- 3.3 % is used in pipeline and distribution.

Pretty popular, pretty handy that natural gas. Hard-working as it is, if natural gas is to be used as a transportation fuel and also generate twice as much electricity in the future and also provide power for the homes, businesses, and industrial products used by the 571 million to 1.182 billion people in the U.S. in 2100 (U.S. Census 2000), then the U.S. will need to produce or import a great deal more natural gas.

As mentioned in Chap. 7, in order to make a drop-in diesel from natural gas, many more Gas-to-liquid (GTL) plants need to be built. There are only five now due to their high cost and limited locations, since they need to be near decades of low-cost natural gas reserves. The largest GTL facility is in Qatar. It cost $19 billion, three times more than projected, but only produces 140,000 barrels/day (0. 17 % of world oil demand of 77,833,000 barrels/day) and makes more money from chemicals than GTL transportation fuel. The energy efficiency of the process used in converting natural gas-to-liquid products is poor, only 58–65 %, far less efficient than oil refining, where about 90 % of energy in crude oil remains in finished products. To justify the cost of a GTL plant, oil prices must remain high and natural gas prices low. Perhaps this is why none of the three plants proposed for the U.S. were ever built.

GTL plants can produce drop-in diesel that can be used without a hiccup by trucks and locomotives. Compressed (CNG) or Liquefied (LNG) natural gas, on the other hand, requires new or modified engines and large tanks. Even with that, this would represent a downgrade for trucks and locomotives. They can go four times further on diesel than CNG, and two times further than LNG, and would need to stop for fuel more often and take more time to refuel.

LNG is only made at 60 sites in the U.S. and there are few LNG import terminals. There are about 170 LNG trucks that can carry 9–13,000 gallons per load to 73 LNG public stations, three-quarters of them in California.

Long distance truckers care a lot about energy efficiency. Fuel is their largest expense (39 % in 2012). Yet few CNG or LNG trucks are being bought despite the low price of natural gas for several reasons: (1) the latest diesel engines are 7.7 % more fuel efficient, (2) there are only 73 public LNG stations, (3) Class 8 CNG/LNG trucks cost about $50,000–$100,000 more than diesel equivalents (NRC 2015), with barely enough time for lower natural gas prices to repay the extra cost of the truck before the truck needs to be replaced, (4) truckers don't want to take the risk that natural gas prices will rise, and (5) LNG needs to be kept at −260° F or it boils off in seven days.

Some predicted truckers would embrace CNG and LNG, and that it would capture 20 % of the truck market. Today in the U.S., only 3.5 % of 10 million medium and heavy duty trucks run on CNG or LNG. In the U.S., less than 0.1 % of natural gas is being used for transportation. The U.S. has only 1 % of the 12 million natural gas vehicles in the world.

Railroads have been trying out LNG and other non-diesel fuel prototype locomotives since 1935. They haven't worked out because they weren't powerful, reliable, efficient, or durable enough; needed tanks too large to fit in locomotives, had questionable safety after a derailment and when fueling, were out of service 15–20 % more than the diesel fleet, needed refueling more often, and lost 12 % of the fuel during fueling (BNSF 2007; TIAX 2010). Diesel locomotives remain the little engine that could.

In addition, railroads stick with diesel because the LNG gas turbine engine alone costs $2 million, as much as an entire diesel-electric locomotive, plus another $1 million per fuel tender car that carries LNG instead of freight (ANL 2002; BNSF 2007). Even if railroads wanted to use it, LNG locomotives and fuel tender cars don't exist, and would take time to develop.

With the exception of the 350 LNG carriers operating in 2014, most ships do not burn LNG (IMO 2009), cannot burn LNG in their diesel engines, and do not want to use LNG which has half the energy density of oil and requires special storage tanks, pipe systems, and handling. Ships burn very cheap heavy and marine diesel, the dregs of crude oil, in highly efficient, highly reliable diesel engines. These fuels do not boil off like LNG. In addition the current LNG refueling infrastructure is inadequate. So although new ships can be constructed to use LNG, very few are being built.

Conclusion

As of now, ships, trucks, and trains have put all their eggs in one basket. They all burn diesel.

Clearly having commercial transportation that can run on one or more fuels would be a good idea. Recent history is replete with repeated oil shocks. But there can be natural gas shocks too, and importing LNG would make the U.S. doubly vulnerable to supply disruptions.

Truckers aren't placing as many bets on natural gas as industry and utilities, so it isn't likely that 20 % of trucks will be running on gas come the day that oil production starts to decline. But if oil declines faster than gas, and natural gas remains plentiful, some trucks will be built or converted to run on CNG or LNG.

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Chapter 11
Liquefied Coal: There Goes the Neighborhood, the Water, and the Air

Coal can certainly be made into a drop-in diesel—a fuel that can be burned in existing diesel engines. It has been done in South Africa for over 50 years by Sasol, where coal is converted into liquid fuel (CTL). Also, China's Shenhua Group recently built the first commercial Direct Coal Liquefaction plant, though the EROI may be low or negative (Kong et al. 2015). Today, South Africa and China are the only nations with commercial CTL plants.

The Earth's coal is very unevenly distributed with half the reserves in the U.S. and Russia and another third in China, Australia, and India. Only these nations are likely to attempt to liquefy coal because of the high cost of CTL plants due to the huge amounts of coal needed—also because coal is heavy and bulky, not as easy as oil to move around the world.

The Future of CTL: How Much Diesel Could Be Made from Coal?

Imagine gushers of liquid coal. If all global coal production were converted to liquid coal, perhaps 17 million barrels a day (Mb/d) could be produced. That amounts to 22 % of current world oil production. If more efficient liquefaction technologies came along, and coal now used to generate electricity and make cement, steel, aluminum, paper, and chemicals were all diverted to make liquid fuels, as much as 54 Mb/d could be made. But roughly 17 Mb/d is more likely because diverting most or all of the coal from other uses to make CTL is not realistic (Höök et al. 2010c).

The other option would be to double coal production to make CTL, but that might cut reserve life in half. In the U.S., there may be 63 years of reserves at current rates of production, but only 31.5 years if we doubled coal production (Rutledge 2011).

The 17 Mb/d of world CTL production is derived from Sasol's *actual* CTL production in South Africa (Höök et al. 2010c), not imaginary, theoretical values, that propose much higher volumes of CTL from coal.

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The thermal efficiency of liquefaction is roughly 50–60 %; hence, only half the coal energy used in liquefaction will come out as the energy available in the CTL fuel (Höök et al. 2014). And there may be other losses. An inconvenient truth about coal is that it is a dirty fuel. If carbon capture and sequestration were to be required, 40 % of the remaining energy in a liquid coal power plant would be consumed.

Liquid coal production is limited by water, which uses six to 15 tons of water per ton of CTL. In the U.S., most of the coal is in the dry states of Wyoming and Montana.

Time, and a lot of it, would be required to scale CTL production up to 17 Mb/d. It takes more than five years to construct a CTL plant, and even more time if rail, water, and pipeline infrastructure is needed (USGAO 2007; NRC 2009). The National Petroleum Council said that the U.S. could produce up to 5.5 Mb/d of CTL fuel by 2030 (NPC 2007). Sasol uses one ton of coal per 1–1.4 barrels of fuel, so a goal of 5.5 Mb/d by 2030 requires 1.6 to 2.3 billion short tons of coal (Höök et al. 2010c). That is twice as much as the 984,842,000 tons of coal mined in the U.S. in 2013 (EIA 2015). It would be reasonable to doubt that coal production could be doubled in 15 years (Höök et al. 2009; Croft and Patzek 2009). Not to be forgotten: 93 % of current U.S. coal production is used to generate electricity, not for transportation fuel.

Finding the capital to ramp up liquid coal is going to be difficult due to the high cost. A theoretical million barrel a day plant sited in Montana coal country would cost from $48 to $160 billion dollars (Patzek 2009), twice as much as a natural Gas-to-Liquids (GTL) plant due to the necessary extra steps to convert solid coal to synthesis gas (NPC 2007).

Public opposition will be strong, not only because of the high CO_2 emissions, but other toxic wastes. Sasol's CTL plants use 45 million tons of coal resulting in 50 million tons of mining waste every year, which contains arsenic, mercury, lead, cadmium, and other toxins that threaten water supplies, health, and ecosystems.

"Green" plants that convert coal and biomass (CBTL) have also been proposed. These are ideally located within 40 miles of both coal and biomass. But dry Wyoming and Montana are not near much biomass, and as previously detailed, there is not enough biomass to go around for all the demands in the future.

World and U.S. Peak Coal May Have Happened, or Will Soon

Were the target of 17 Mb/d world CTL production to be achieved, there are reasons to believe that flow might not last for long.

The conventional wisdom is that there are centuries of coal left. Most Intergovernmental Panel on Climate Change (IPCC) scenarios show coal production steadily increasing to 2100.

But there are scientists who question this.

Just like oil, the easy, high-quality coal with the most energy per ton (anthracite and bituminous) was mined first. Much of the remaining coal is low-energy lignite with about as much energy as wood or slightly higher energy subbituminous coal. And as with real estate, “Location, location, location” is paramount. A great deal of remaining coal is “stranded”, far from harbors, rail lines, or roads.

U.S. reserves are supposed to be the largest, 28 % of world reserves, but they haven’t been measured since 1974, making the current 250-year-supply questionable. In 2007, the National Research Council recommended the USGS reassess reserves, because their own investigation could not confirm 250 years of reserves, and that 100 years was more probable (NRC 2007). Coal production in Illinois has declined to half of what was mined 20 years ago, yet Illinois is still credited with having reserves nearly the size of Montana.

Since the NRC report, U.S. geological surveys of two key mining regions showed rapid depletion of high-quality coal (Heinberg and Fridley 2010; Luppens et al. 2008; Höök et al. 2010), and another found that only 4 to 22 % of the original resources are break-even economically recoverable (Luppens et al. 2009).

Nathan Reaver, in the International Journal of Coal Geology, found that coal reserves have been greatly exaggerated in many regions and nations. Especially the U.S., where the maximum tonnage extracted is likely to be between 2009 and 2023, with 2010 the most likely year. If the energy content is taken into account, then the most likely peak was 2006, or somewhere between 2003 and 2018 (Reaver et al. 2014), or perhaps already happened in the late 1990s (Heinberg and Fridley 2010).

Even the U.S. Energy Information Agency (EIA) has acknowledged that the estimated recoverable reserves can’t technically be called “reserves” because extraction profitability hasn’t been determined.

Tad Patzek, former chairman of the Department of Petroleum and Geosystems Engineering at the University of Texas, Austin, found that energy-contentwise, global coal peak may have occurred already in 2011. By 2050, remaining coal will provide only half as much energy as today, and carbon emissions from coal will decline 50 % by 2050. Patzek used the same Hubbert methods that successfully predicted peak oil to come to this conclusion (Patzek et al. 2010).

Other scientists predict that global coal production, in tons, may peak between 2026 and 2034 (Mohr et al. 2009), 2015–2020 (EWG 2013), or 2020–2030 (Höök et al. 2010a). Predictions for peak U.S. coal also vary. U.S. coal, in tons, may have peaked in 2008 (EWG 2013), or will by 2050 (Höök et al. 2010b). Or peak coal could be 50 years or more away if coal gasification, which has been around since 1800, were improved or other technologies invented.

Sooner or later, the peak amount of coal production will occur, and supplies decline thereafter. Yet, economists and even the Intergovernmental Panel on Climate Change believe that this is centuries away because they assume that all coal resources will become exploitable reserves. Like natural gas, not all coal is created equally. Some of it is high-energy anthracite and some it is low energy lignite. Some of it is near existing harbors or rail, and some is far from any means of transportation to anywhere it could be used. Currently, coal deeper than 4000 ft is usually not economic to mine. Yet, coal that is buried 8000 ft down is treated one and the same as readily minable coal reserves on the world’s balance sheet.

Do we really have a century or centuries of coal remaining? It is more likely that coal over 2000 ft deep will be uneconomic and that reserves are only half of what is stated than that all of the world's remaining coal will be exploited. Especially when oil begins to decline—since there is a lot of oiliness in coal production. This is the bad news; but for those of us concerned about climate, the good news.

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Chapter 12
Who Killed the All-Electric Car?

Electric cars (EV) seem like the best thing since sliced bread. The liquid fuels they don't burn make more oil available for heavy-duty trucks, ships, and planes. It should not escape our notice that there are very few electric trucks and no electric ships or planes. Later in this book, we'll explore those possibilities, but for now, suffice to say they aren't so easily electrified (Long 2011).

Inventors began making batteries (and fuel cells) circa 1800, yet there are still very few all-electric autos. The 2006 documentary film, "Who Killed the Electric Car", blames automakers, the oil industry, the U.S. government, and faults the intelligence of consumers.

But that's not who did it. Drum roll … It was the battery! Not much suspense in so quickly revealing that, but it's still a good story. The real mystery, however, is not *who* did it, but *why* batteries aren't powerful enough, despite 215 years of research. The lead–acid battery hasn't changed much since its invention in 1859. Li-ion batteries hold over two times as much energy by weight as the first commercial batteries sold in 1991 but are nearing their limit. The energy density of other commercial rechargeable batteries had risen only six-fold since the lead–nickel batteries from the horse and buggy era of over a century ago (Van Noorden 2014a).

Yet, hope springs eternal. A better battery has always been just around the corner:

- 1901: "A large number of people … are looking forward to a revolution in the generating power of batteries, and it is the opinion of many that the long-looked-for, lightweight, high capacity battery will soon be discovered" (Hiscox 1901).
- 1901: "Demand for a proper automobile battery is so crying that it soon must result in the appearance of the desired [battery]. Everywhere in the history of industrial progress, invention has followed close in the wake of necessity" (Electrical Review #38. May 11, 1901. McGraw-Hill).
- 1974: "The consensus among EV proponents and major battery manufacturers is that a high-energy, high power-density battery—a true breakthrough in electrochemistry—could be accomplished in just five years" (Machine Design).
- 2015—An Internet search for "battery breakthrough" gets 38,700 results, including: *Secretive Company Claims Battery Breakthrough, 'Holy Grail' of*

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Battery Design Achieved, Stanford breakthrough might triple battery life, A Battery That 'Breathes' Could Power Next-Gen Electric Vehicles, 8 Potential EV and Hybrid Battery Breakthroughs.

So Why Isn't There a Better Battery?

That black box may look simple, but inside is a churning chaos of complex electrochemistry as the battery surges between being charged and discharged over and over again, which is hard on a battery. Recharging is supposed to put Humpty Dumpty back together again, but over time the metals, liquids, gels, chemicals, and solids inside clog, corrode, crack, crystallize, become impure, leak, and break down.

The vehicle battery palette is limited to the 118 elements in the periodic table. Most can be ruled out because they're radioactive (29), inert noble gases (6), don't conduct electricity, are rare earth or platinum group metals (23), too toxic (9), not found on earth (2), too scarce, too expensive, or too heavy.

The laws of physics have imposed theoretical maximum energy limits on batteries due to the properties of the elements in the periodic table (Zu et al. 2011). The highest possible energy density would be an almost 6-V Lithium–Fluorine battery (Li/F_2). But despite decades of research, no Li-F battery exists because it is very toxic, not rechargeable, unstable, unsafe, and inefficient, the solvents and electrolytes can't handle the voltage, and ultimately lithium fluoride crystallizes and stops conducting electricity.

The second highest, Li–air (Li/O_2), theoretically has an energy density approaching gasoline, but in practice might be twice as good as current Li-ion batteries. They're still experimental, with low power, poor cyclability, and need pure O_2, which requires an oxygen tank. A prototype is probably over 30 years away (NRC 2015b).

It is not easy to make a better battery. Here are just some of the qualities required to achieve the holy grail of a better battery:

1. Small and lightweight to take up less space and give vehicles a longer range
2. High specific energy density (energy stored per unit of weight and unit of volume) to deliver energy for hours and give vehicles a longer range
3. High power density for acceleration and capture of regenerative braking energy
4. Ability to be recharged thousands of times (cycle life) while retaining 80 % of energy storage capacity in real-world driving so that the battery will last as long as the vehicle: 10–15 years.
5. Ability to be recharged fast, in 10 min or less, rather than overnight
6. Not harmed by overcharging, undercharging, or over-discharging
7. Reliable and robust, able to tolerate vibration, shaking, and shocks
8. Made from inexpensive, common, sustainable, and recyclable materials
9. Safe: doesn't explode, catch on fire, and has no toxic materials

10. Doesn't self-discharge when not in use
11. Performs well in both low and high temperatures
12. Needs minimal to no maintenance
13. Much cheaper than the battery packs now that run about $450 per kWh, or $35,000 for a 78 kWh battery

Basically, the ideal battery would be alive and able to self-heal, secrete impurities, and recover from abuse, like cartoon characters who are back to normal seconds after explosions, falling off of cliffs, or sawn in half. That's what the world needs, the Wiley Coyote battery!

Pick Any Two, there is no "One Size Fits All." Batteries are a lot like the sign "Pick any two: Fast, Cheap, or Good." Although li-ion batteries are ahead of lead–acid, nickel–cadmium, and nickel–metal hydride due to their high-energy storage, none of the Li-ion chemistries so far offer an ideal combination of energy density, power capability, durability, safety, and cost (NRC 2013). On top of that, lithium batteries lose charge even when idle, and don't perform well in cold and hot temperatures.

You always give up something. Battery chemistry is complex. Anode, cathode, electrolyte, and membrane separator materials must all work together. Every time you improve one thing, you might harm other essential features. Higher energy densities come from reactive, less stable chemicals that often result in non-rechargeable batteries, are susceptible to impurities, or catch on fire. Storing more energy may lower the voltage.

Battery testing takes time. Every time a change is made, dozens of parameters need to be retested to make sure that the improvement didn't break or lessen other essential properties. Even with accelerated testing, it takes a long time to see if the new battery will last at least 7 to 15 years. First, each battery cell is tested, then a module containing multiple (battery) cells, and finally the battery pack.

"You have to optimize too many different things at the same time" according to Venkat Srinivasan at Lawrence Berkeley National Laboratory (Service 2011).

Conflicting demands. For example, "If you want high [energy] storage, you can't get high power," said M. Stanley Whittingham, director of the Northeast Center for Chemical Energy Storage. "People are expecting more than what's possible."

Be skeptical of battery breakthrough announcements. It typically takes 10 years to improve an *existing* type of battery, and it's expensive. You need chemists, material scientists, chemical and mechanical engineers, electrochemists, computer, and nanotechnology researchers (Borenstein 2013). Then, another five years to develop, test, and manufacture a new car that uses the new battery.

Van Noorden (2014b) at *Nature* magazine reported on why a recent, highly hyped aluminum battery breakthrough may never appear in your phone or car. Not mentioned were a few obstacles such as having only one-fifth the energy of li-ion batteries, that lab prototypes were so tiny that when scaled up for real use, the aluminum battery may not recharge as quickly, and the much larger electrodes might crack. Even if it clears these hurdles, commercial aluminum batteries could be 15 years away. Van Noorden said the story of batteries is one of the small startups promising way more than they can deliver in order to get investment money (Van Noorden 2014a). A good example is Envia Systems, which raised $17 million from GM and other investors on a battery that never panned out (LeVine 2015).

Shortening the decade-long development process. "We need to leapfrog the engineering of making of batteries to find the next big thing," said Vince Battaglia, a Lawrence Berkeley National Lab battery scientist.

Incremental improvements won't electrify cars and energy storage fast enough (DOE 2007). Scientists need to understand the laws of battery physics better to make a big leap. To do that, researchers need to be able to observe what's going on inside a battery at an atomic scale in **femtoseconds (0.000000000000001 s)**, build nanoscale tubes and wires to improve ion flow, and devise complex models and computer programs that use this data to predict what might happen when some aspect of a battery is changed.

The laws of physics and properties of elements in the periodic table mean there's only so much rechargeable electrochemical energy you can theoretically cram into a black box. No matter what you do, that always will be orders of magnitude less than petroleum (House 2009).

Alas, there are additional limits. The energy provided by battery (cells) is cut in half within a battery pack as energy is lost from cell to module to battery management system. Battery packs consist of modules with batteries overseen by a battery management system that uses energy to monitor and cool cells down. Elaborate control systems prevent a shorter battery life by making sure all cells have the same thermal history and protect against too fast charging or discharging. Each cell's voltage, temperature, and internal resistance is monitored. The cooling system prevents thermal runaway or fatal destruction of cells at temperatures over 120 °F (NPC 2012).

Further energy is drained by air-conditioning, heating, lighting, dashboard displays, music, and GPS, all of them reducing the range.

Lithium is famously flammable, but many battery types can catch on fire, so the battery pack is encased in steel for protection. A significant amount of weight and volume also come from the monitoring and cooling systems. In the end, the battery pack is so heavy, that for every pound of the battery pack, up to 1.5 pounds of structural support for the body and chassis is required. Because of this, an electric vehicle with a 300 mile range might weigh three times more than a conventional car (Shiau et al. 2009; Wagner et al. 2010).

All-Electric Autos

Electric vehicles are not likely to take off until they have at least a 200 mile range and cost considerably less than the $71,000 Tesla S, which can go 265 miles with an 85 kWh battery pack. Tesla's battery is 3.1–5.3 times larger than competitors, whose vehicles travel 62–93 miles on 16–27 kWh batteries and it costs from $25,700 to $43,300 (plugincars 2015).

To achieve greater ranges will require batteries with three times greater energy densities at one-third the current cost per kWh (NPC 2012). What are the prospects for that? Researchers think lithium-ion battery energy density might be improved by 30 % at best (Van Noorden 2014a, b). EVs are also held back because there are only 53 million garages (Lowenthal 2008) in the U.S. for 253 million vehicles (Hirsch 2015).

So far, most of the increases in the driving range of all-electric cars come from the use of lightweight materials, aerodynamics, and tires with less rolling resistance.

Early adopters are buying all-electric vehicles, but the masses are hanging back. One reason: The time it takes to recharge an all-electric vehicle battery is a non-starter. Overnight, or even an hour wait, won't cut it. Unless batteries can be developed that can be recharged in 10 min or less without degradation, cars will be limited largely to local travel in an urban or suburban environment (NRC 2013). In this respect, electric vehicles are the turtle and gasoline vehicles are the hare. Electric vehicles charge about 1,000 times slower than refueling with gasoline (NAS 2008). To recharge faster than that requires a level 3 charger costing $15,000–$60,000 which would make fast charging of electric vehicles more expensive per mile than gasoline (Hillebrand 2012).

To be competitive in electrified vehicles, the United States also requires a domestic supply base of batteries, and key materials and components such as special motors, transmissions, brakes, chargers, conductive materials, foils, electrolytes, and rare earth metals, most of which come from abroad. The supply chain adds significant costs to making batteries, but it's not easy to shift production to America because electric and hybrid car sales are too few, and each auto maker has its own specifications (NAE 2012).

We may notice a new Tesla, but there aren't that many all-electric vehicles on American roads. At current rates of transition from gasoline to all-electric cars and trucks, with 123,000 electric vehicles sold in 2014 (InsideEVs 2015), it would take over 2000 years to replace the nation's fleet of 253 million vehicles), and require 980 TWh of electricity (25 % of 2008 generation) taking about 15 years to build (Smil 2010). Cost is not a minor impediment. The average income of an electric car owner is $148,158, and of a new gasoline car $83,166, far above the median household of $51,929 (NRC 2015a).

Hybrid battery-gasoline cars have been far more successful, with 3.6 million sold in the U.S., since 2000. Hybrid batteries last much longer than all-electric batteries because they are not discharged deeply, perhaps 30 % of the useable capacity. That gives hybrid batteries a significantly longer life than plug-in electric batteries, which discharges from 70 to 80 % of their capacity for more range, reducing battery life.

In many ways, Americans are spendthrift when it comes to energy. As a nation, we have been willing to spend trillions of dollars fighting multiple wars in the oil mecca of the Mideast. We spend billions per year to protect oil sea lanes and chokepoints. And when it comes to why we buy a particular vehicle, Americans rank fuel efficiency 11th in terms of importance (NRC 2015b, Table 9.4). The vehicles we actually buy reflect that. Until 2007, 85 % of the cars on American roads got less than 22 mpg, and when gas prices dropped in 2014, hybrid sales went down and SUV sales went up.

In the end, it's not just the lack of a better battery but American consumers who are unwilling, or unable to afford energy efficient cars (and light trucks) of any kind.

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Chapter 13
Can Freight Trains Be Electrified?

High-speed passenger rail is all the rage, but when it comes to electrification of America's freight trains there's no buzz, almost total silence. Europe and Russia have electrified freight trains, so why doesn't the U.S.?

European and Russian governments paid for electric passenger rail, and electric freight trains joined the party. Europe's electric rail is 80 % passenger trains, which have priority over freight, making cargo delivery less reliable. That's one of many reasons why Europe's freight trains hauled 60 % of all cargo in 1950 but only 8 % now (Vassallo 2005).

In America, freight railroads are built and maintained by private industry. Absent public tax dollars, U.S. freight railroads can't afford the tens of trillions of dollars electrification would cost. Even so, American rail kicks European and Russian freight train's butt, hauling 45 % of freight in the U.S. (by ton-miles) at less cost, much faster, and more energy efficiently (Economist 2010; Eurostat 2015).

U.S. rails can't be beaten. Trains can go across the North American continent from Mexico to Canada, unlike Europe, where different rail widths (gauge) and different electric catenary systems stop trains at borders. Besides, American trains are *already* electric. Diesel-electric locomotives use their diesel engines to power electric motors instead of using electricity generated by nonrenewable coal, natural gas, and nuclear power.

Electric rail makes more sense for passenger trains, which stop, start, accelerate quickly, and travel at high speeds. An energy efficient freight train is the exact opposite: accelerate slowly, stop or start as little as possible, and travel at slow speeds to reduce aerodynamic drag.

U.S. railroads are as likely to electrify as elephants are to buy hang gliders and jump off of cliffs. It would be economic suicide since they can barely afford to run, maintain, and grow what they have. Besides, they're only using 2 % of all U.S. transportation fuel, which is 18 % of their overall $64.1 billion annual budget. Even when oil prices skyrocketed in 2008, there was no move to electrify (AAR 2012; Iden 2009; NPC 2012).

Rail is highly invested in diesel-electric locomotives that cost $2 million each and are expected to last for 30 years. All-electric locomotives cost about $5–$10 million each (SCAG 2012; Pernicka 2010) and may not be powerful enough to

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haul America's freight trains, which are much heavier and longer than in other nations.

Even the cost of a fleet of electric locomotives pales in comparison to the cost to install a power distribution system to electrify the rails. More power generation, new transmission lines, substations, and overhead wiring above the tracks would be required. America has 200,000 miles of freight rail. Even if only the most traveled tracks carrying 21 million tons per year were electrified, distribution would need to stretch for 50,000 route miles plus cover nearby sidings, parallel, and terminal tracks (NPC 2012).

Exactly how much it would cost to electrify America's freight trains is hard to know, because most estimates for electrification are for passenger rail. The only freight electrification project being considered in the United States is a $28 billion dollar project in the Los Angeles area combining electrified passenger trains with trains that carry containers from ports to inland distribution centers about 30 miles away (SCAG 2008, 2012).

California's 520 miles of planned high-speed passenger rail is estimated to cost $68 billion (Nagourney 2014), or $130.7 million per mile which means $26.7 trillion for 200,000 miles of freight rail. Since freight trains need a great deal more power than passenger trains, the cost would be *much* higher (Table 13.1).

Overhead wires are mandatory, because a third rail for freight trains is too dangerous, unable to deliver the high power needed, and easily clogged with leaves and ice. That's a shame, because overhead wires are expensive, and raising them much higher than any other nation to accommodate stack trains (two containers high) is likely to add to the cost (plus raising bridges and tunnels). Just the overhead wires for 200,000 miles of railroad tracks would cost $800 billion [$3.98 million/mile = the average of $3.96 million (SCRRA 1992), $4.55 million (Caltrain 2008), $3.42 million (Metrolinx 2010)].

An electric locomotive is an awesome beast. Just one 4400 horsepower locomotive is the electrical equivalent of 2200+ plug-in hybrid vehicles being recharged. So the current U.S. fleet of 25,000 locomotives would use as much electricity as 55 million electric cars, and it's not clear where all this electricity would come from. Passenger trains need only 25 kV lines, but freight needs at least 50 kV to minimize the number of substations (Iden 2009).

Table 13.1 Train power demand

Rail operation	Power demand per train in Megawatts (MW)	Equivalent horse power
Light rail	1	<1400
Heavy commuter	3–4	4000–5400
High-speed intercity	4–6	5400–8000
High-speed trains (TGV)	8–10	10,700–13,400
European freight	6–10	8000–13,400
U.S. freight trains	6–24	8000–32,000

Source Iden (2009)

To electrify the 2000 miles of rail from Chicago to Los Angles, at least 1500 MW would be required. This is equal to three large conventional power plants (FRA 2009), so to electrify our major routes with 160,000 miles of tracks, you'd need the equivalent of 240 power plants (some of which already exist). Additional power infrastructure also would be needed since railway electrification load is one of the most difficult for an electric utility to cope with, and parts of the power grid have little spare capacity (Boyd 2009b). Would trains need to stop at peak demand times so that people could turn on their lights and do so without blowing up the grid?

D'oh! Why Electrify? Diesel-Electric Locomotives Already *Are* Electric and *More Efficient Than All-Electric Locomotives!*

U.S. trains are powered by diesel-electric locomotives. Diesel-electric is the way to ride. Instead of sucking electricity via hundreds of miles of overhead wires from a distant power station, diesel-electric locomotives have their own power generation plant on board—a 40 % efficient diesel engine (Hoffrichter, USDOE). The electricity generated onboard drives traction motors to move the wheels, with no mechanical connection between the engine and wheels, which is far easier, cheaper, and more efficient than pure electric locomotives (James 2011; Smil 2013).

Electric locomotives get their electricity from inefficient power plants with a 32.8 % average efficiency, plus another 6 % loss over transmission and distribution lines. By the time the energy gets to the train wheels, you've lost 75 % of the energy, giving electric locomotives an overall efficiency of 22.9 %, which is 7.1 % less than diesel-electric locomotives (see detailed calculations).

These electric locomotive calculations do *not* include the energy to construct new power plants and thousands of miles of overhead wires, substations, electric loading and unloading of train car and other infrastructure to deliver electricity to all-electric locomotives or replace diesel-electric locomotives.

Detailed Calculations. Every Step Reduces Efficiency
30 % Efficient Diesel-electric Locomotives: 40 % diesel engines × 92 % generator × 98 % rectifier × 92 % electric motor × 95 % transmission × 95 % traction auxiliaries (Hoffrichter 2012)

22.9 % Efficient Electric Locomotives: 100 % electricity at locomotive × 95 % feed cable × 95 % Transformer × 97.5 % Control system/power electronics × 95 % electric motors × 95 % transmission × 95 % traction auxiliaries (Hoffrichter 2012) × 32.8 % overall average energy efficiency of electric power generation plants × 92.4 % transmission and distribution losses (NRC 2015)

Electrify with Batteries? Been There, Done That. It Didn't Work Out

Railroads have been experimenting with electric locomotives since 1838. In America, 126 battery-operated locomotives have been built, 14 of them battery only, whereas the others had gas or diesel engines as well. Not a single one was a long-haul locomotive. They all were local, yard switcher locomotives that assembled and disassembled trains where they could easily be recharged or fixed when batteries failed entirely.

What have we learned? What all of these experiments revealed is that batteries weigh a lot, break easily, are difficult to maintain, have little usable power, and often have to be replaced, going beyond expected costs. When pushed beyond their safe depth of discharge, or damaged after a jarring, hard coupling, the train might stop running, not such a great thing in a switching yard, and definitely not cool if an all-battery long-haul locomotive broke down in the middle of nowhere, blocking the trains behind it (Iden 2014).

Energy storage devices are too expensive and incapable of moving a train a reasonable distance (Vitins 2011). Just one railcar can weigh 286,000 pounds, so a 100 railcar train could weigh 28.6 million pounds, the weight of over 190,000 150-pound people. Batteries don't have enough oomph—enough power and energy—to move that much load.

Batteries for regenerative braking? Locomotives have very little room to accommodate regenerative braking batteries. Instead, a battery tender car coupled-and-connected to the real locomotive, or a separate locomotive devoted only to energy storage would need to be built (Iden 2014).

It is hard to capture regenerative braking energy, because much of the time the train isn't using the brakes because the ground is flat or slightly undulating. Centuries of railroad engineers have sought out and purchased the flattest routes, and invested a lot in building them. Only a small minority of tracks known as "hogbacks" can capture regenerative braking, which are steeper uphill and downhill grades about the length of the train. And a mile-long train can be going downhill, uphill, and level at the same time, requiring train engineer to play the two types of braking system used on trains like a concert pianist.

The 80 trains going down California's steep 25-mile Cajon pass grade every day, one of the few grades this steep in America, could generate as much as 1200 kWh per train with regenerative braking. The downside is that this would require 525 tons of lead–acid batteries. That's a lot of deadweight to haul when the train returns uphill to the Cajon pass, and is not economically viable because it would only save 70 gallons of fuel (Painter 2006). If you tried to haul fewer batteries to save on weight and cost, complex systems to monitor the batteries to prevent them from overcharging would be required.

Other Issues with Electrification

Single point of failure. Many events can stop the flow of electricity, causing severe and expensive congestion on the most trafficked routes. What could stop an electrified rail line? Landslides, earthquakes, high winds, hurricanes, washouts, heat waves, lightning (Smith 2008), locomotive mechanical or electric failure, wires getting struck by vehicles at road crossings, lack of power due to not enough substations, sabotage, and terrorist attacks (NRC 2012). In those circumstances, electric-only locomotives will be stuck dead on the tracks, and need to be rescued by diesel-fueled locomotives (SCAG 2012) creating costly and severe congestion on many heavily traveled routes.

Even if the electric grid were beefed up, occasions would occur when it might not be powerful enough to meet the high energy demands of freight trains. For example, when there are several trains near each other, peak demand, or the locomotives need a lot of power to go uphill, with perhaps 22 MW or more needed.

Political and institutional hurdles. The SCAG rail electrification project in Los Angeles will be difficult to implement since it encompasses six counties and 197 cities that will want to have a say in the project. Now multiply the complexity and number of affected local, state, and government agencies by tens of thousands when considering a national-scale project to electrify rail. The Los Angeles project is child's play.

Diesel-electric locomotives can't be beat. Mechanically, diesel-electric engines keep getting better, last a long time, are rugged enough to handle rough patches of rail, and can be rebuilt. Many locomotive engines achieve the equivalent of one million miles before overhaul, equal to 36,000 MWh (USDOE 2002).

Electrification makes more sense for passenger trains servicing highly populated areas since electricity is useful for rapid acceleration (not at all necessary for freight trains), high speeds, and frequent stops. Freight trains are the opposite—they travel outside of densely populated urban areas, are slow, rarely stop, and need power, not acceleration. Speeding up non-aerodynamic freight trains wastes energy. Since most of what's being hauled doesn't spoil, freight doesn't need to get anywhere soon. There are about five derailments a day in North America. Imagine the damage a 25 million pound electric train derailing at 100 mph would cause, plus the added costs of the overhead wires being pulled down. High speeds would also wear out tracks out faster, requiring expensive maintenance.

Nations that electrify their freight rail lines often do so because they don't produce petroleum, and, in some cases, oil-producing countries that want to export oil will electrify (NPC 2012).

Europe's Freight Trains Are Inferior. Why Copy Them?

In much of Europe, borders are open and the Euro is a common currency. Ironically, trains can't travel between countries because in Europe there are three types of rail gauges, four different voltages, eleven different ways of hooking to the overhead wires, and half their rail lines aren't electric.

U.S. freight trains haul about seven times more freight by weight than in Europe due to continent-wide interoperability with the same rail gauges across America, Canada, and Mexico, and railroads share their tracks and other infrastructure with one another. This is why American rail freight is the cheapest in the world, half as much as in Europe and Japan (Iden 2009).

Electrify Just the Busiest Corridors

Let's say the oil available to power diesel locomotives becomes scarce or expensive. Would it then make sense to electrify just the busiest American corridors?

Here's what would happen: Interoperability would be reduced if electric and diesel locomotives had to be swapped at every electric and non-electric border, with double the staff to maintain both electric and diesel infrastructure. This would delay trains long enough to shift some freight to trucks, because swapping locomotives, pressurizing brake systems, and safety inspections would take 3–6 h (SCAG 2012).

That's why the railroads have insisted that the only acceptable solution is dual locomotives that are both electric and diesel. One small problem: There is no freight dual-locomotive yet (Boyd 2009a, b). To convert an existing diesel-electric locomotive, you'd need to add a 50 kV step-down transformer to the engine (or auxiliary car) weighing 20,000 pounds that takes up 480 cubic feet of space, plus supporting equipment in a locomotive that's already at the maximum height, width, length and weight limit. Even now, there is little space left in a locomotive due to equipment added to comply with EPA tier 4 emission standards. Oh, and you want regenerative braking? That'll take even more space (Iden 2009).

Conclusion

Why electrify U.S. freight rail? It already is electric. Instead of electrifying rail, which uses only 2 % of all U.S. transportation fuel, we should discourage light-duty cars and light trucks, which guzzle 63 % of all transportation fuel and give the fuel saved to diesel-electric locomotives.

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Chapter 14
All-Electric Trucks Using Batteries or Overhead Wires

Since trucks are the chariots driven by the Gods of Stuff, in a fossil-free world it would sure be divine to have all-electric trucks.

Trucks don't have a lot in common with Tesla. The Tesla gets some of its high mileage from low aerodynamic drag (0.24), not the battery. Nothing personal here, but a truck is not a sleek beauty queen of the road. Trucks will always be a blocky mass of air resistance (0.60–0.65) and lose 20 % of fuel energy or more to drag when they travel over 50 miles per hour.

Hybrid diesel-electric (battery) trucks that capture regenerative braking will save some fuel, but are best for trucks that stop and start frequently like garbage trucks and buses, not the trucks on highways that don't stop often enough to recharge a hybrid battery.

It is much harder to develop hybrid systems for trucks than cars, since they are expected to last 15 years or travel 1 million miles (compared to an auto lifetime of <10 years), and travel in more extreme conditions of temperature, vibrations, and corrosive agents (NRC 2015).

Trucks are like postal carriers: Neither snow nor rain nor heat nor gloom of night stays these couriers from the swift completion of their appointed rounds. A truck would have a problem living up to that creed if powered by a Li-ion battery. Li-ion, the state of the battery art, does not function well in cold and hot temperatures, which can shorten their lifespan, or even ruin them (AAA 2014; Calstart 2013a; Pesaran 2013).

Battery-Electric (BEV) Trucks

Batteries capable of moving a big truck would be behemoths, far too heavy and large to be practical. One European study calculated that a truck capable of going 621 miles hauling a maximum payload of 59,525 pounds would need a battery weighing as much as 55,116 pounds, which is 93 % of the legal road weight limit there, and take up a quarter of the space in a 40 ft. container (den Boer et al. 2013).

Another study found that the battery to move a 33,000 pound truck would weigh 17,500 pounds, have a 500 mile range with an efficiency of 23 %, and cost so much

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it would never pay for itself. An improved diesel truck using the technology available today could go 1300 miles with an efficiency of 39 %, and pay for itself within a year (DOE 2011).

The Port of Los Angeles explored the concept of using an all-electric battery drayage (short-haul) truck to transfer freight between the port and warehouses, but rejected them because they could go at most 100 miles a day before needing to be recharged, half of the minimum 200 miles needed. The short range was due to the need for a 350 kWh battery that weighed 7700 pounds and reduced payload too much. The 12 h or more to recharge the battery was another deterrent. Ultra-fast 30 min recharging was considered too risky since this might reduce battery lifespan, and bearing the cost of replacing these expensive batteries was out of the question (Calstart 2013b).

WAAAAY Too Expensive

For all trucks, with current battery technology, not enough fuel is saved to justify the cost of an expensive battery pack. A diesel delivery truck costs $65,250 now, which is $35,000–$182,000 less than an all-electric battery truck, and $207,000 less than a hydrogen fuel cell (FCHEV) delivery van. If you add in the infrastructure cost of electric or hydrogen service stations, the cost difference is even higher. Clearly BEV and Hydrogen fuel cell (FCHEV) delivery, drayage, and long haul trucks cost too much to be competitive with diesel trucks now (Table 14.1).

Calstart also looked at $234,090 drayage trucks running on compressed natural gas (CNG) aided by a 150 kWh battery ($47,250). Since a used drayage truck can cost as little as $3000, this is clearly not economic. Plus there is an additional cost of $8400 per truck for the CNG fueling station (Calstart 2013b).

Typical e-truck battery warranties now are just three years but need to be a minimum of six years to be acceptable. Cold and hot weather, ultra-fast charging, overcharging, discharging beyond recommended depth, damage to delicate battery

Table 14.1 Comparison of costs for different types of trucks using three types of propulsion systems, Delivery & Long haul costs in 2010 US$ (den Boer et al. 2013, Tables 15–18, 21). Drayage and infrastructure cost (Calstart 2013b, Tables 4.7, 4.11, 4.20). FCHEV are far from commercial both in cost and technology

Type of truck	Diesel	BEV $400–800/kWh	FCHEV
Delivery	$65,250	$100,000–247,000 250 kWh battery	$272,260
Drayage	$104,360 Used: $3000	$307,890 350 kWh Battery $110,880	$226,361 60 kWh Battery
Long Haul	$107,610	$1,000,000–2,000,000 2500 kWh battery	$598,678
Infrastructure cost per vehicle	N/A	$25,000	$3350

management systems and other electronics from rugged roads can decrease battery life as well.

Despite massive local, state, and federal subsidies, many medium-duty electric truck and battery companies have gone out of business. Smith Electric received a $32 million grant for 500 Newton e-trucks, but went bankrupt in late 2013 despite a $66,402 subsidy per vehicle (Chesser 2013, 2014; Cassidy 2014). Navistar received $39.4 million for 950 electric delivery trucks but is in financial trouble and discontinued its electric van in March 2013 (Truckinginfo 2013). A123 made batteries for Smith Electric, but went bankrupt in March 2012 despite a $263 million dollar grant (Cohan 2012). Eaton has discontinued sales of diesel-electric hybrid drive systems as well (Eaton 2014).

Additional Costs

There is an alternative to a truck driver twiddling his thumbs, waiting for his electric truck to be recharged. Why not battery swapping stations? The problem is money. A truck battery swapping station might cost over $4 million, based on a $3 million cost for a car station (Berman 2011). The swap stop for trucks would need more storage and operating space for hundreds of large battery packs and for many large trucks to pull into. And perhaps a little more elbow room for the truckers!

Added electric generation might also be needed. Consider this frame of reference. The entire Los Angeles Metropolitan Transportation Authority light and heavy rail system consumed 489,000 kWh/day. But just 2500 BEV trucks that go 100 miles a day would need 625,000 kWh/day (250 kWh battery * 2500 BEV).

To charge just one 25 kWh battery pack in five minutes requires a power flow rate of 300 kW, equal to the peak power demand of a 100,000 square foot office building (NPC 2012).

Trucks Running on Overhead Wires (Catenary)

Since the battery-electric trucks the Port of Los Angeles was considering for drayage were impractical and could only go half of the required 200 miles, the port looked at using an overhead wire (catenary) system on the I-710 highway.

Trucks running on catenary systems are expensive, because they need equipment to use the catenary as well as a second propulsion system to deliver cargo after leaving the overhead wires. That is on top of the catenary system capital cost of $5–$7 million dollars per mile (Carpenter 2012) (Fig. 14.1).

A catenary is not just for any truck. It is hard to imagine putting wires over the 360 million acres of U.S. cropland for electric tractors, or the cost of doing so. Likewise many other trucks operate off the grid for logging, maintaining transmission lines, pipelines, railroads and dams.

Fig. 14.1 I-710 Siemens demonstration project with one mile catenary system. Cost $13,500,000. *Source* AQMD (2015)

Catenary systems do exist. In San Francisco, they are used by 273 trolley buses and 200 tramcars powered by overhead lines spaced about ten minutes apart. A great deal more power would be needed for the more than 40,000 drayage trucks that travel the 24 miles of the I-710 corridor every day, just seconds apart.

Conclusion

Trucks don't yet ride the roads on battery power. That day remains down the road, and indeed, over the horizon.

The very best batteries today are far too heavy, expensive, short-ranged, and take too long to recharge to be adopted by medium and heavy duty trucks. It would take decades to replace or alter millions of diesel trucks to run on overhead wires, and we do not know whether today's electric grid, or a future renewable grid, can produce enough electricity to power them. Our quest for battery-powered trucks must keep going, and going, and going …

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Chapter 15
Overview of the Electric Grid: Herding Lightning

At a U.S. Senate Hearing, Senator Ron Wyden of Oregon asked energy conservation advocate Amory Lovins if the Administration's FY2007 budget request of $942-million for the Advanced Energy Initiative, $1.18-billion for energy efficiency and renewables, and about ten times that amount for various nuclear energy programs would do anything to deal with what President Bush called our "national oil addiction."

Lovins replied "I'm sorry to say no," and pointed out these proposals would not reduce oil imports because the programs were for technology that would generate electricity, which has nothing to do with oil. "This confusion between oil and electricity, conflating them both into 'energy,' bemuses energy experts the world over who assume responsible U.S. officials must understand these fundamentals; yet such jumbled formulations persist" (Senate 109–412 2006).

Cars, trucks, trains, and ships all use oil, a liquid fuel. Not electricity.

Electricity does not solve an imminent transportation oil crisis because the nation cannot, in the blink of an eye or in a few years or probably decades, convert or build trucks and locomotives to operate with power from millions of miles of overhead wires or many millions of tons of batteries.

But if the national plan is to transition, over many decades, to operate transportation with electricity, then we have to start with a clear understanding of the present U.S. electric grid, and how it has evolved.

The grid began a century ago with utilities that did everything in their region. In the beginning, they were like islands. The utilities owned the power plants and the transmission system delivering electricity over the web of wires, controlling it like a master chef at a stove turning the flame up and down to exactly match supply with customer demand. When the utility screwed up, the results were worse than a charred steak—a blackout could occur.

Flash forward to today. No utility is an island. They are all interconnected. The U.S. and Canadian grid is often called the world's largest machine, valued at more than $1 trillion with over 6000 power plants, 200,000 miles of high-voltage lines, 390,000 thousand miles of transmission lines, 55,000 substations, 6 million miles of distribution lines, all connected to communication, computer, and control systems.

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Over the decades, deregulation added further complexity to the grid. 65 % of utilities that were "single chefs" responsible for electricity end to end, from power plant to light switch, were broken up into thousands of entities. They became specialists—services include electricity buyers and sellers, power plants owners, resource planners and schedulers, distribution providers, and reliability authorities.

Compounding this complexity, the electric system has many federal, regional, and local governing agencies. These entities work within the three grids of the continental U.S.: The 11-state Western (WECC), Texas (ERCOT) its own island of power, and the 36-state Eastern interconnection (EC). Within these grids are other regions, and over 110 balancing authority areas. The chefs who run them may have the most important job to keep the grid up: Demand by all of us who use electricity to toast our waffles, cool our homes, and make aluminum must be exactly balanced by the supply of electricity being produced and coming to us over that grid. Supply and demand is balanced by operators who constantly interact with each other, calling up power plants to increase or decrease power, and wheeling power to hither and yon across the grid.

Buyers and sellers move electricity across vast regions in ways the system was never designed for, and many private utilities seek profits by cutting back on maintaining transmission, research and development, and staff.

This cost cutting has led to the majority of equipment being 50–70 years old, which makes it three to ten times more likely to fail, and more vulnerable to natural disasters, cyberattack, and terrorists (Willis et al. 2013; NRC 2012). The more maintenance and replacement are deferred, the more times the lights will go out.

The American Society of Civil Engineers gives U.S. energy infrastructure a grade of D+ because "America relies on an aging electrical grid…. Ongoing permitting issues, weather events, and limited maintenance have contributed to an increasing number of failures and power interruptions, from 76 in 2007 to 307 in 2011…. Congestion at key points in the electric transmission grid has been rising over the last five years, which raises concerns with distribution, reliability and cost of service…. This congestion can lead to system-wide failures and unplanned outages" (ASCE 2013).

The grid is not just an inanimate flow of electrons through wires, transformers and so on. Batteries of highly skilled workers make the grid go. Half are eligible to retire within the next 10 years. Many utilities see a lack of skilled employees as their biggest problem, with few electrical engineers being trained to replace them since pay is so much higher outside of the utility field. In addition, few power engineering programs are offered at universities (NRC 2012).

Three kinds of power keep the U.S. grid in balance:

1. Baseload power, mainly from coal (40 %) and nuclear (20 %) which can always be counted on to generate the minimum level of demand around the clock.
2. Intermediate "load following," wherein natural gas plants or hydropower kick in at daybreak when factories and coffee pots rev up, then shut down at night.
3. Natural gas "peaker" plants and hydropower, with the unique and indispensable ability to go from standby to full-blast almost instantly when there is high

demand, such as on hot days for air-conditioning which uses enormous amounts of electricity. Peakers also are essential for balancing the grid because of the intermittent nature of wind and solar. More wind and solar would not be possible without peakers to quickly balance the grid.

The twenty-first century grid that lights our life could never have been imagined 150 years ago when the first isolated DC power systems were built in the 1880s. It is as delicate as it is vast. Power production generators throb in unison, pushing power out at nearly the speed of light across transmission lines, like monks chanting "Ohm." Disturbances self-correct as magnetic forces and the rotational inertia of generators naturally revert back to the right frequency and voltage—a good thing, since variations just a few percent off of 60 Hz can damage equipment, cause a local power outage, and even a cascading blackout if transmission lines and other equipment are overloaded (Lerner 2014). In 2003, over 55 million people were affected by a blackout in the Northeast.

Planning for reliability starts when power plants are scheduled for the next day based on weather forecasts and historic load patterns. There must be the right mix of baseload, intermediate, peaking, and other electrical services scheduled. When cities wake up, the show begins as machines, devices, and lights are turned on.

As demand surges, sellers send power to distant buyers. Operators can't control where electricity flows—it takes the path of least resistance across all available paths, so operators scramble to keep the grid balanced, making corrections as soon as imbalances occur.

With so many chefs, it is truly remarkable that what is perhaps the largest and most complex machine ever created is up 99.8 % of the time. If electricity were used to run our transportation systems, the electric grid would be severely challenged to provide enough power, especially as destabilizing intermittent power provides more and more of generation, which will be explored in the next chapter.

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Chapter 16
The Electric Grid Trembles When Wind and Solar Join the High Wire Act

If we are to have electric transportation—I'm not talking about golf carts here—we are going to have to grow the grid. To use electricity as a transportation fuel, we'll need more electricity, and perhaps a national grid. While sustaining current uses, how much supplemental transportation energy would it be possible for such a grid to support?

The grid of the future will be very different from today. Currently, 87 % of U.S. electricity generation comes from nonrenewables: 67 % fossil (natural gas and coal) and 20 % nuclear. How would that evolve to an 80–100 % renewable electric grid?

Electricity is an amazing all-you-can-eat buffet available at the flip a switch, but a wasteful one, with two-thirds of the power lost as heat from the nonrenewable thermal plants that provide 86.2 % of our electricity (Table 16.1), and another 6–10 % is lost at the power plant (other than heat loss) and over transmission lines. In the end, only 24–28 % of the power makes it to the banquet.

As you can see in Table 16.1, coal generation declined from nearly half of electricity generation in 2005 to 38.7 %, and natural gas increased from 19 to 28 %.

Where Will Tomorrow's Power Come from?

Not nuclear. U.S. nuclear power plants are old and in decline. By 2030, U.S. nuclear power generation might be the source of just 10 % of electricity, half of production now, because 38 reactors producing a third of nuclear power are past their 40-year life span, and another 33 reactors producing a third of nuclear power are over 30 years old. Although some will have their licenses extended, 37 reactors that produce half of nuclear power are at risk of closing because of economics, breakdowns, unreliability, long outages, safety, and expensive post-Fukushima retrofits (Cooper 2013).

New reactors are not being built because it takes years to get permits and \$8.5–\$20 billion in capital must be raised for a new 3400 MW nuclear power plant (O'Grady 2008). This is almost impossible since a safer 3400 MW gas plant can be built for \$2.5 billion in half the time. What utility wants to spend billions of dollars and wait a decade before a penny of revenue and a watt of electricity is generated?

A.J. Friedemann, *When Trucks Stop Running*,
Energy Analysis, DOI 10.1007/978-3-319-26375-5_16

Table 16.1 Percent of total electricity generation 2005, 2014, and 2030 (frozen at 2014 total of 4092 TWh). EIA Table 7.2a Electricity Net Generation Total 2005 and 2014. 2030 is my estimate

	Coal	Gas	Nuclear	Hydropower	Wind	Biomass	Oil	Geothermal	Solar
2005 % of generation	49.6	19	19.3	6.7	0.4	1.3	3	0.4	0.01
2014 % of generation	38.7	28	19.5	6.3	4.4	1.6	0.7	0.4	0.5
2030 % of generation (my estimate)	26	40.3	9.8	6.5	13.2	1.6	0.7	0.4	1.5

Source http://www.eia.gov/totalenergy/data/monthly/pdf/sec7_5.pdf

Opposition to new nuclear plants is strong because of the risk of proliferation of nuclear weapons, lack of permanent waste storage (Alley et al. 2013), and safety, especially after Fukushima and Chernobyl. If a major accident happens, more likely every year after a plant is 20 years old (Hirsch et al. 2005), opposition might grow strong enough to delay, or even stop new projects. Generation IV reactors are decades from being commercial. For new nuclear power in California to happen, costs need to go down, the Price Anderson Act needs to be extended beyond 2026 to indemnify operators against accidents exceeding $10 billion, and by law, a licensed national nuclear waste repository needs to exist before reactors can be built (CCST 2011). In addition, uranium production may peak as soon as 2015 (Dittmar 2013) or 2020–2035 (EWG 2013).

Not coal. Many think king coal is at retirement age, with its best days behind it in the U.S. Production here has possibly peaked both in tons and coal energy content. Of the remaining roughly 325 GW coal generation capacity, 58 GW is expected to retire. If the EPA Clean Power Plan is executed, up to 101 GW will be retired, and that would reduce coal-generated electricity from 38.7 to 26.6 % of the nation's total by 2030 (EIA 2015b). This is because new coal plants won't be permitted to be built without carbon capture and storage (CCS), which is at least 10 years away from being commercial, and likely to be too expensive if it ever becomes commercial (House 113-12 2013). Coal power advocates blame government and environmentalists for the decline. But cost is a larger problem for coal. Right now, coal can't compete with natural gas. Coal is over the hill.

Coal and nuclear plants have other problems too. Both need to run flat-out to pay back their high capital, operation, and maintenance costs. They're built to run steadily around the clock, since it takes 4 to 8 hours for them to warm up, synchronize their turbines with the grid, and heat large volumes of water to raise steam for turbines. They are built to provide baseload power and not built to quickly ramp up and down to balance wind and solar power. When forced to do so because wind and solar have first rights of generation, or to avoid negative prices, they not only earn less revenue to pay back their high capital and maintenance costs, their equipment can be damaged, shortening the plant's life span (CEC 2008; IEA 2011; Wald 2014).

Not Natural Gas. I calculated that if a third of coal and half of nuclear generation need to be replaced with natural gas, then this finite fossil would provide 40.3 % of electricity generation in 2030. In 2014, 8149 billion cubic feet (bcf) of natural gas was used to provide electricity, which would rise to 11,860 bcf, or 44 % of all natural gas consumed in the U.S. in 2014. Production may rise, but this is not a certainty. If tax credits, cash grants, and aggressive depreciation for wind and solar aren't available, then the tripling of wind and solar generation in 2030 will be less than predicted, increasing the share of natural gas for power generation even more. That's not good news for the many other sectors that use natural gas.

There Is No Free Lunch

Nuclear plant construction was greatly restricted in the 1980s and since then because of environmental concerns. Because electrical demand has been growing, most of the increased demand has been met by coal. But now the concern is CO_2 emissions, and coal is the unwanted king. Under new environmental pressures, electricity is shifting to natural gas, which may or may not release fewer greenhouse gases. This will lead, in time, to depletion of natural gas. So our children or grandchildren may one day castigate us for a depletion of the premium feedstock for their much needed nitrogen fertilizer and other important chemicals. Unquestionably, this leaves less natural gas for fertilizer, plastic, heating, and industrial uses. Or, of principle interest here, for transportation.

Drought and sea-level rise will reduce fossil and nuclear power generation. When our needs are projected into a future that will presumably be characterized by climate change, we will have additional challenges. Hurricanes shut down oil extraction facilities in the Gulf of Mexico, and sometimes destroy or damage rigs, as happened to the very expensive Thunder horse rig. Thermal generation depends on tremendous amounts of water for cooling. Both drought and floods reduce nuclear, coal, and natural gas power generation.

Not hydropower. America the beautiful and powerful has 2540 U.S. hydropower dams. There are no places left in the continental U.S. to put very large hydropower dams. Run-of-river and retrofitted small dams could contribute 22 GW beyond the current 77 GW capacity, which has not increased much since 2000 (NETL 2012a, House 113-12 2013). Hydropower is limited. Let us count the ways: By season, rainfall and snowmelt, reservoir size, drought, evaporation, flood control, drinking and agricultural water, ecosystem health, and fisheries. Hydropower has a great virtue in being able to be turned up or down quickly, but operating in this way generates very large stresses on the fish, insect and other ecosystem components below. Water may run as long as time itself, but hydropower plants have an average life span of 60–80 years, failing when the reservoir fills with sediment, concrete settles, cracks or erodes, and with extreme floods.

Not marine hydro-kinetic (MHK) power. Hydro-kinetic almost seems like it's up against an immutable law: You can't fight Mother Nature. Variable MHK power, such as wave, tidal, and ocean currents is not commercial due to too frequent destruction by tides, storms, hurricanes, lightning, icing/ice floes, large waves, marine growth, and corrosion. To transform MHK from pipe-dream into kilowatts, other forces need to be overcome: Very high capital and maintenance costs, low efficiency, locations too far from urban centers and the grid, and conflicts with fishing, ship navigation, aquaculture, marine sanctuaries, and nearby ports. Hydro-kinetic also needs a lot of space. To generate 1000 MW of wave power in the rough North Sea, the Wave Dragon Energy Converter would need to be 124 miles long (NRC 2013).

Not offshore wind, which has the same issues as hydro-kinetic. In the U.S., 90 % of the optimal offshore wind sites—where the winds blow regularly and with gusto!—are in water too deep for current technology. Offshore turbines are too big to travel on land and must be launched from new $1.3 billion port facilities with $100–250 million vessels capable of lifting 757 ton turbines (Navigant 2013; NREL 2010b).

Not geothermal. There is not a lot of steam near the surface that can be readily tapped outside of Iceland. Geothermal relies on rare, near-surface geologic formations, needs lots of water and nearby power lines and roads. It provides only 0.4 % of U.S. power, most of it in California and Nevada. Untapped remaining sites are usually too small to justify transmission lines, too expensive, or lack water (CEC 2014; CCST 2011; NREL 2012a, 2013).

Not biomass. As discussed earlier in this book, biomass doesn't scale up enough and transportation has higher priority, more valuable freight to haul than biomass for electricity. Wood, the fuel of preindustrial societies (Perlin 2005), is half of renewable power in the European Union now, much of it imported from North America since Europe has little timber to burn (Economist 2013).

That leaves onshore wind and solar PV to save the day… with a little help from their fossil and nuclear friends, while they're still around. It will take time, since renewables are likely to grow slowly from 2018–2030 (DOE/EIA 2015) because tax incentives might go away once current renewable portfolio standards are met. There has been considerable discussion about whether the EROI of wind and solar are sufficient to support modern society, especially if backup systems are included (see Weissbach et al. 2013, 2014; Prieto and Hall 2013; Palmer 2013; Raugei 2013; Raugei et al. 2015). Charles Hall and other scientists believe this issue is not resolved yet, especially if the high costs of batteries or other backups are factored in.

Wind turbines come in many shapes and sizes, and their numbers are growing. Yet, they provide only 4.4 % of U.S. electricity, 181,791,000 MWh. That's equivalent to the power generated by 32,428 2-MW wind turbines (a). To supply half of America's power with wind, another 332,600 2-MW turbines are needed (b).

(a) 32,428 wind turbines: 181,791,000 MWh/5606 MWh power/year per turbine = 2-MW wind turbines × 0.32 average U.S. wind capacity × 24 h × 365 days).
(b) 365,000 wind turbines: 4,092,935,000 MWh U.S. electricity 2014/2 = 2,046,467,500 MWh/181,791,000 MWh provided by wind = 11.26 × 32,428.

Wind and solar are intermittent. The wind blows free—but about 70 % of the time, not at all, or enough to turn the blades, or blows with too much gusto. The sun can be depended on to set in the evening and rise in the morning, but clouds are more whimsical, creating crescendos and lulls of solar output.

All the while, the grid must remain in balance.

Intermittency

A big problem with electricity is that you have to use it when you produce it. If you dump too much electricity into a grid, you get load imbalance, blackouts, and can even melt equipment. Storing energy seems easy to those of us who do not use much in flashlights and car batteries, which are well-developed technology.

The problem is scale: All the batteries in the world can store less than 10 min of world electrical production (Gates 2010).

In the 11 states of the Western grid, if 35 % wind and solar were integrated, their intermittency would require 100 % backup from conventional sources such as natural gas and large hydro to maintain system reliability (NREL 2010a).

So to get 100 % of electricity generation from wind, which is only blowing a third of the time on average (the capacity factor) requires building three times more reliable capacity to keep the system stable and backup wind when it isn't blowing (CCST 2011). Right now that is mainly done with fossil and nuclear power. But in a 100 % renewable system with little or no natural gas, you'd need to build massive amounts of energy storage and three times as many wind turbines to charge the backup energy storage batteries.

So our 365,000 wind turbines need to be multiplied by at least three (plus energy storage) for a grand total of 1,095,000 wind turbines in a mostly renewable grid, and somehow connect even the most distant wind turbines in the remote regions of the Great Plains. That seems like the game is stacked against wind and solar, and that someone is moving the goalposts. Why three times more capacity? Read on.

The capacity factor is how much power is actually generated, which is always a fraction of the theoretical maximum amount of power that could be obtained if the wind always blew at the optimum speed or every day was the sunniest day of the year.

Since the average wind capacity factor over a year is around 33 %, you need to build three times as much wind to provide power to the electric grid, and somehow connect them, if the goal is to replace nuclear and fossil generation, which theoretically could have 100 % capacity factors if grid operators chose to run them around the clock and needed no down time for maintenance. But that's just an average, and there will be days when 300 % of what is needed would be generated and the excess would need to be stored or curtailed, and other days when less than 33 % was generated. The triple overkill is for reliability, to compensate for transmission losses, and make it more likely to have half of electricity power generation when needed.

The record year for the most wind generation ever built in the U.S. was 2012, equivalent to 4819 2-MW turbines. If we tilted towards windmills and built that many a year starting in 2016, it would take 220 years to build 1,095,000 of them to generate half of our electricity. Since their life span is 20 years, even more time and windmills would actually be needed for construction (Davidsson et al. 2014).

The word "wind" belies the fact that these machines are not light and airy. Nor easily popped up. Each 2-MW wind turbine weighs 3,375,000 pounds (Guezuraga 2012; USGS 2011), equal to 102 18-wheeler trucks. The wind may be free, but wind turbines surely are not.

Solar photovoltaic (PV) and concentrated solar power (CSP) provides only 0.45 % of U.S. electricity in 2015. The most solar built occurred in 2013, 9285 GWh. If this amount of solar is built every year starting in 2016, solar would reach half of 2014 electricity generation of (2,046,468 GWh) in 220 years.

The EIA has been providing statistics on solar PV and thermal capacity factors since August of 2014 (Table 16.2). For the last year, the average capacity factor of solar PV has been 28.3 %, Concentrated Solar Power (CSP) 22.2 %, and wind 31.5 %. So at least 3.5 to five times more solar capacity needs to be built to make up for the low 28.3 and 22.2 % capacities, and to make up for a solar PV panel degradation rate of 0.8 % (mean 0.5 %) per year. That would take 1100 years, plus PV panels will need to be replaced every 25 years, the average length of their warranty (Jordan et al. 2013). Also, a great deal of energy storage will be needed for times when the sun isn't shining.

Table 16.2 Capacity factor percent for U.S. Solar Photovoltaic, Solar thermal (concentrated solar power), and wind from August 2014 through June 2015

Year	2014					2015						
Month	8	9	10	11	12	1	2	3	4	5	6	7
Solar PV %	31.9	32	26.7	23.4	15.6	18.9	25.9	29.4	33.9	33.9	34.2	33.8
Solar CSP %	25	25.9	20.8	13.4	5.5	4.6	15.5	23.6	31.8	31.1	34.5	35.1
Wind %	22.5	26	31.5	42.2	30.4	31.3	34.2	31.5	37.6	35	28.2	27.6

Source (EIA 2015a)

The Electric Grid Trembles When Wind & Solar Join the High Wire Act

Grid operators are ringmasters. They have had to cope with the mismatch between demand and supply, and over decades have learned what the patterns are, and how to turn power plants up and down, on and off, accordingly. But wind goes from a whisper to a roar when storms arrive (Halper 2015), a bucking bronco that gets increasingly hard to manage and control the more wind and solar penetrate as a percentage of overall power (IEA 2013).

So far, wind and solar power penetration is so small that operators can balance it with natural gas peaker plants, dispersing excess generation across a larger region, more frequent scheduling (15 min or less), (pumped) hydropower, or curtailment.

A National "Super-Grid"?

America has three grids that cover the lower 48 states. They are only loosely connected, and have minimal ability to transfer power between them. A national U.S. super-grid is thought by many to be needed because the Eastern states, where most of the population resides, have very little renewable power. Also, renewable resources are concentrated in different areas of the U.S., with Western states having the most hydro and geothermal power, Southwestern states the most solar PV and solar thermal (CSP), and Midwestern states the most biomass and wind (NREL 2012b).

High wind penetration especially depends on a large balancing area, so a calm cloudy Nebraska can be balanced by a windy Wyoming and sunny Arizona. Unfortunately, most good to superb wind (class 4+) is stranded because these sites tend to be in states with low population density and usually far from cities. It's not just coincidence. Cities arose near flat farmland, usually far from the best wind resources on hills, mountain ridges, and other high ground where wind speeds are highest. Flat areas can be good too, the smoother the better to reduce friction and keep the wind moving. That's why eastern Iowa can capture some of the powerful winds blowing across the Great Plains—the corn crops don't stop it (IEC 2015).

Because of this stranding far from transmission lines, very little of the potential power that could be harvested from wind will actually be realized. Even if we built legions of wind mills, they wouldn't contribute as much power as existing fossil and nuclear generation. The National Renewable Energy Laboratory added up the undeveloped prime and non-prime renewable power potential in one of the country's three major grids, the 11 Western interconnection states (WECC). Don't think you can read this report and get in first on the wind rush. The best, low-cost areas *have already been fully developed* in California, Oregon, Utah, and Washington. The remaining non-prime resources will cost more and be less productive. Total potential future renewable generation was 378 TWh (148 TWh prime, 230 TWh non-prime)

(NREL 2013). This is less than the current 481 TWh of fossil and nuclear power production in these states (EIA 2013).

Despite the need for a larger balancing area, a national grid in America is unlikely. There are downsides: the potential of a national blackout from instability, cyber-attack, terrorism, and aging equipment (NRC 2012). A national grid would continue to require a long-term stable economic and political environment.

Although a national grid can increase stability, this isn't always the case. Operators have fine-tuned data and familiarity with their own regions, but can't see adjoining systems well enough to reliably detect impending extreme events and take countermeasures quickly (CEC 2008). Size doesn't always increase reliability. Greater size provides more pathways for local disturbances to propagate, which can lead to complex chains of cascading failures (Morgan et al. 2011). In addition, increased loading of transmission lines and transformers without increasing investment to expand this infrastructure (Clark 2004), and poorly planned generation and transmission capacity (Blumsack 2006) has the potential to cause additional widespread blackouts.

Think of what it would take for wind to provide half of America's electricity. Think of what it would mean for the American landscape, and what it would mean for the grid. You'd need 1.1 million 2-MW wind turbines. Each would require 170 acres of wind to harvest (NREL 2009). Together, they would cover 290,860 square miles, the equivalent land mass of Illinois, New York, Florida, Pennsylvania, Virginia, and Kentucky. This would require at least 50,000 miles of new transmission lines, with many up to 1500-mile-long underground, multi-gigawatt links from the Great Plains to the coasts (Smil 2010) costing millions of dollars per mile. It can take 14 years to build transmission lines to distant renewable sites, due to lawsuits and negotiations with land owners and political jurisdictions (DOE 2002; Wald 2008). Are the windmills of your mind spinning?

Wind and Solar Don't Replace Conventional Power, They just Add to the Blaze

Wind and solar add logs to the fire. But they cannot replace conventional plants, because they can't be counted on. It would be like expecting 3-year-olds to harvest strawberries. Adults are going to end up doing most of the work.

In the IEA world energy outlook 2012, New Policies scenario, it was calculated that 450 GW installed capacity of wind in 2035 would only produce 112 GW of power, given the ebb and throb of wind. Even that is of little use to the grid. When the grid needs power, it must have it immediately, *now*. Wind (and solar) cannot always be counted on like fossil and nuclear power on peak demand days and at peak demand hours. The IEA New Policies scenario calculated that wind could be counted on only 5 % of the time (*the capacity credit*) for just 22.5 GW at peak demand times. That means an additional 89.5 GW (112–22.5 GW) of reliable fossil, nuclear, or biomass power is needed to back up wind power. The concept of capacity credit for wind is not intuitive, and hard to get your head around. But it this simple: The more you replace conventional power plants with wind, the more you depend on wind. And, the more you depend on the wind, the less you can depend on it.

Great Britain's office of science and technology estimated wind could be counted on reliably only 7–9 % of the time if the overall penetration of wind power ever reached 50 % (GBHP 2014). So if 25 GW of wind capacity were built to replace 25 GW of fossil and nuclear plants (life span 35–50 years), and the capacity credit of wind at peak demand was 5 GW, then an additional 20 GW of fossil and nuclear plants would be needed for backup, with nearly double the energy generation as before (45 GW). In regions where peak demand occurs in the winter, the capacity credit of solar power is zero, because peak demand occurs after dark. And thus the stark reality: "Investment in renewable generation capacity will largely be in addition to, *rather than a replacement for power stations*" (GBHL 2007). It hardly seems fair.

Intermittency is the fly in the ointment. Backup fossil and nuclear power plants must be online, burning fuel while waiting to step in when wind or solar power drops, and back off when they increase. Since nuclear and coal run as baseload and can't quickly ramp up or down without damage, natural gas plants and some hydropower are called upon. Areas heavily dependent on coal or nuclear power might need to limit the amount of intermittent generation because of the damage done, slow ramp rates, and lack of stability if too much fossil generation is idled (NETL 2012b).

How Much Intermittent Wind and Solar Penetration Can the Grid Handle?

Claims that Denmark has 32 % wind penetration come with a caveat. They ignore the fact that excess power is dispersed across a large area and stored in Norwegian hydropower reservoirs. Likewise, Iowa may generate 28 % of its power from wind, but because it is shared with 12 other states, wind power penetration is 5 % in all those states collectively.

The more flexible a system, the more variable power can be used. In California, in 2014, 11.8 % of *in-state* power generation was intermittent, 5.3 % solar and 6.5 % wind, easily balanced with the whopping 61.3 % of power from flexible natural gas and 7.1 % large hydropower, and by sharing the power with the ten other states in the Western grid. California in-state renewable power also came from biomass 3.4 %, geothermal 6.1 %, and small hydro 1.2 %, for a grand total of 29.6 % renewables in all. California does not generate as much power as it consumes, and imports an additional 33 % of power from the other ten states in the Western grid (CEC 2015).

Spain has the highest intermittent renewable penetration at 25 % (20 % wind, 4.9 % solar). This is done with a huge excess of installed power, hydropower and natural gas plants, frequent scheduling, a very sophisticated control center, excess electricity exports to France, Morocco, and Portugal, and less demand from customers (due to financial decline in Spain).

Since power supply must match demand at all times, as wind penetration increases, the need for accurate forecasts becomes increasingly important. Kevin Forbes argues wind forecasting errors are much greater than are being acknowledged. If wind penetration increases, more accurate forecasts will be needed to prevent blackouts (Forbes et al. 2012).

Wind and solar penetration may be limited to 55–61 %. Beyond that, the grid can become unstable. This limit was derived from a study of the Western grid (WECC) in the U.S. To reach this level of penetration would require improvements in grid transmission, sharing power between balancing areas, and 400 MW of energy storage (NREL 2014).

Conclusion

How far can we go down this stop-and-go road? Europe, especially Germany, wants to go 100 % renewable electricity. California 50 %. Even though most 100 % renewable scenarios see wind and solar as providing at least 80 % of electricity, their penetration may be limited to less than that. Limits include the stability of the grid, lack of a national grid, inability to scale wind and solar to 80 % of power, a dearth of energy storage, enough biomass to balance power, and inaccurate forecasts.

Wind provides only 4.4 % and solar 0.5 % of U.S. electricity now. Wind is unlikely to scale up to more than 13.2 %, and solar to 1.5 %, by 2030. Development could slow as subsidies end, Renewable Portfolio Standards are met, or another recession hits. Even if we continue building wind and solar at the current record rates, it would take centuries to reach half of our total power generation from wind and solar. Why not a crash program? We need to look before we leap. Accelerating development would be unwise until the maximum penetration level of intermittent power is known. Likewise, eminent domain at all levels of government to build necessary transmission lines should be in place. And we'd want to know whether there is enough natural gas production in the U.S. and/or available import LNG to balance the grid.

So in addition to facing an energy crisis, the potential for an electricity crisis exists as well unless energy storage can come to the rescue. Energy storage—what a dull name for such a heroic role.

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Chapter 17
The Electric Blues: Energy Storage for Calm and Cloudy Days

Ships are not electric, and probably never will be. How would you glide a container ship across the ocean on batteries? Where would you plug in to recharge?

U.S. trains already are electric, carrying their own onboard diesel-electric power stations. You don't need nor want the electric grid to make a train go choo–choo.

Trucks are too heavy for batteries. Even the energizer bunny hasn't figured out how to make a truck go. Yet, one inevitable day, world oil supplies will have declined to the point that the cost of moving freight onboard diesel trucks will become prohibitive in more and more situations.

Come that day, a revamped electric grid could help keep trucks rolling. What if the grid was weaned off of natural gas to give it to trucks? If push comes to shove, trucks could run on compressed or liquefied natural gas combustion engines.

But taking natural gas away from the grid would be tougher than taking Budweiser away from an alcoholic. The grid depends heavily on natural gas, with 28 % of U.S. electricity now provided by natural gas, and an even greater percentage if coal and nuclear power plants retire. Most critically, natural gas peaker plants will play an indispensable role on the grid, allowing operators to balance supply and demand from variable wind and solar power.

How do we transition the grid to rely less on natural gas and, more and more, on wind and solar? Energy storage could open the door to that future.

Steven Chu, former U.S. Energy Secretary under President Obama, described the growing need for storage: "As renewable energy becomes an increasingly larger fraction of total energy, the cost of storage becomes part of the cost of renewables. Sometimes the wind does not blow and the sun does not shine. At the 50 % level you'll need energy storage" (Moskvitch 2015).

Many scales and means of energy storage are needed, from millisecond bursts to balance the grid to weeks of sustained storage during seasons when there is little wind or solar power.

A.J. Friedemann, *When Trucks Stop Running*,
Energy Analysis, DOI 10.1007/978-3-319-26375-5_17

More Wind Power and the Short-Term Storage to Make that Happen

The Pacific Northwest National Laboratory calculated the cost of energy storage devices for balancing the grid if wind power reached 20 % of electric generation across the United States. The cost was $54–$170.6 billion. Storage would fill spans ranging from milliseconds up to an hour. Not 2 hours, not a day, and not a week—that will cost you extra. In billions of dollars, the options examined included $54.03 NaS battery, $63.85 flywheel, $81.62 Li-ion battery, $116.61 redox flow battery, $125.06 demand response (car PHEV batteries), $130.24 pumped hydro storage (PHS), $135.48 combustion turbine (CT), and $170.62 compressed air energy storage (PNNL 2013).

If natural gas grew scarce, areas with plentiful hydropower could balance fluctuations in wind and solar power during times when water is plentiful and not being diverted to other uses such as agriculture, fisheries, and cities. But hydropower is unevenly distributed. The top ten states account for more than 80 % of the nation's total hydroelectric power, as shown in Fig. 17.1. In a blackout when all other power generation has failed, hydropower is also the very best resource to restart the grid. They call it a "blackstart."

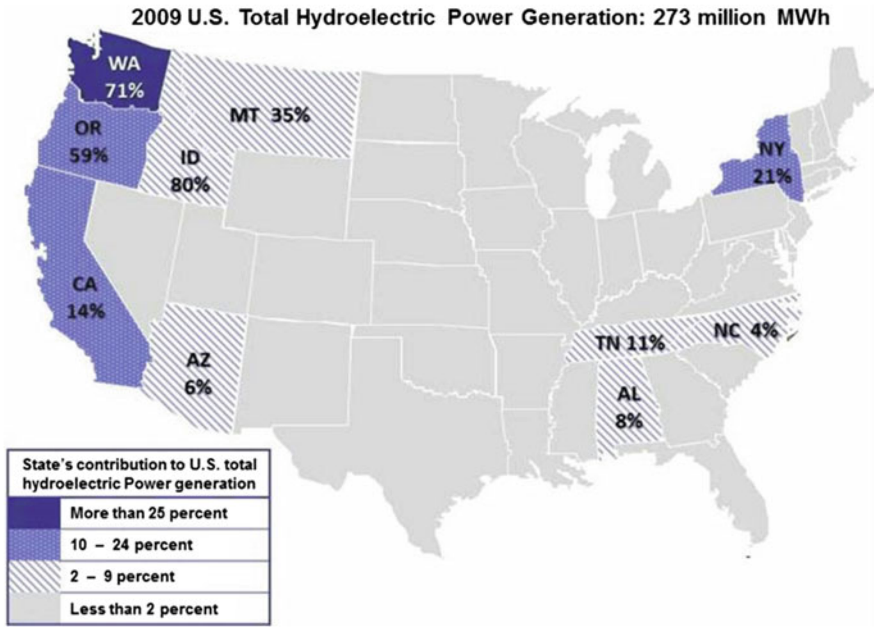


Fig. 17.1 Top 10 hydropower-generating states and their reliance on hydropower for electricity. Washington generates over 25 % of all U.S. hydroelectric power and 71 % of Washington's electric power generation. *Source* Homeland Security (2011). Dams and Energy Sectors Interdependency Study

Longer Term Storage

Intra-hour balancing—milliseconds to 1 hour of storage—isn't enough. Many hours of backup power will be needed since, unfortunately, over two-thirds of total wind power in the U.S. happens outside the 9–5 peak weekdays maximum demand (Baxter 2005).

Peak solar generation is at high noon, which is not the same time of day as peak people demand. For example, in New England the morning demand starts at 5 am and ramps up to 9 am, stays that high until 5 pm, and then reaches an even higher evening peak from 5:30 to 7:30 pm when people come home (EIA 2011).

A much bigger problem is that wind and solar are seasonal, requiring massive storage to solve the "gigawatt-day" problem of days or weeks when renewable generation is insufficient to meet demand, even after all available load flexibility and short-term storage resources have been deployed (CEC 2011; CCST 2012).

Imagine a future in which wind and solar supply up to 100 % of U.S. electricity. You would need to store hundreds of hours of power (Houseman 2014). Winds are highly variable. Seasonal wind—March comes in like a lion, goes out like a lamb—might require 200 hours of storage, which could clearly be done only with very inexpensive storage media, such as water or air (Cavallo et al. 1995).

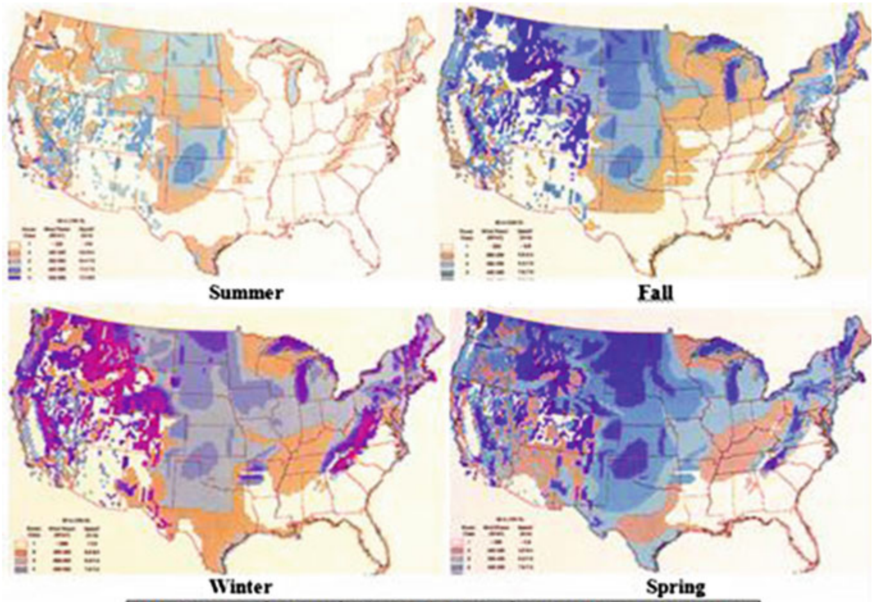
Solar is also highly variable, not just day and night, but intense in the summer and not so much in the winter. A thought experiment: If solar power alone generated enough electricity over a year in the U.S. to meet demand, demand would exceed generation in winter in the ERCOT grid and the PJM, MISO, and CAISO regions of the eastern grid, and also in the summer in ERCOT and PJM due to heavy use of air-conditioning. To overcome seasonal solar, each region would need differing amounts of storage—ERCOT would need 16 Terawatt hours (TWh), California 21 TWh, and MISO 54 TWh. By comparison, the U.S. uses 11.12 TWh of electricity a day.

Clearly, solar generation alone would never happen, but this study does imply that long-term storage will be necessary with a very large portion of variable renewables. Especially since the patterns are often the same across the country, which means that a national grid would not be able to fill in the deficiencies of other regions. Houseman concluded that the energy storage needs for an all-solar U.S. would be 275 TWh (Houseman 2013), clearly an impossibility in any time frame we can imagine.

Wind will not be able to help solar power out much in summer. There is little commercial-level wind (class 3+) across the lower 48 states in summer (Fig. 17.2).

In August, the average wind capacity factor across the U.S. was about 22 % in 2013 and 2014 (EIA 2015). But averages can be deceiving, since much of the U.S. dips below 22 % in summer (Fig. 17.3).

Figure 17.3 paints a picture of seasonal wind patterns across America. Check out California, where the peak and valley of wind power generated, the capacity factor, varies by 30 % from summer to winter. Even with all that additional wind power in the summer, it still is not enough to compensate for the additional electricity needed



Wind power	Class	Density (W/m2)	Speed Range m/s (mph)
	1	<200	<5.6 (12.5)
	2	200-300	5.6 – 6.4 (12.5-14.3)
	3	300-400	6.4 – 7.0 (14.3-15.7)
	4	400-500	7.0 – 7.5 (15.7-16.8)
	5	500-600	7.5 – 8.0 (16.8-17.9)
	6	600-700	8.0 – 8.8 (17.9-19.7)
	7	>800	>8.8 (19.7)

Fig. 17.2 Wind at 50 m. *White* and *orange* are not commercial. *Source* Maps 2-12 through 2-15 wind resource estimates in the contiguous US. http://rredc.nrel.gov/wind/pubs/atlas/maps.html#2-12

during the summer, when air conditioners crank up across the state. A study looking at how California could reach 33 % renewable power considered replacing the California portfolio of renewables with Wyoming wind power, which has a much higher capacity factor, but this would require *adding* 957 MW of natural gas peaker plants, because Wyoming wind doesn't blow at California peak demand times in the summer (NREL 2014).

Solar power is seasonal as shown in the monthly and geographic variability of sunlight in Fig. 17.4. The average capacity factor (energy actually produced compared to potential) of solar concentrated solar power (CSP) was 21 % and solar photovoltaic (PV) 28.3 %, but over a year, solar capacity varied quite a bit (as shown in Table 16.2):

- CSP capacity ranged from 4.6 % in January 2014 to 35.1 % in July 2015.
- PV capacity ranged from 15.6 % in December 2014 to 34.2 % in June 2015.

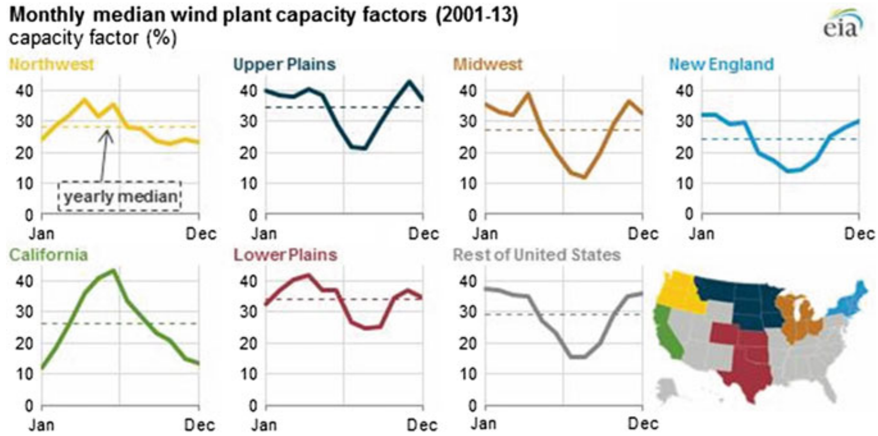


Fig. 17.3 Wind generation seasonal patterns vary across the United States. February 25, 2015, U.S. Energy Information Administration, Forms EIA-860 and EIA-923

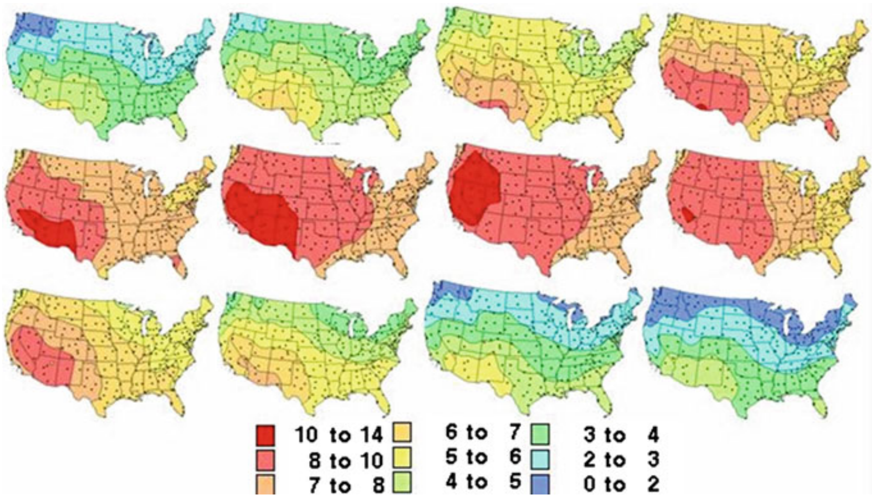


Fig. 17.4 Average daily solar radiation per month January–December 1961–1990 kWh/m^2/day. North–South axis tracking flat plate. U.S. Solar Radiation Resource Maps: Atlas for the solar radiation data manual for flat plate and concentrating collectors

When the Oil Age ends, post fossil fuels, wind, and solar will need to provide 50–100 % of electric power, since they have by far the greatest generation potential.

Most of the studies on 80–100 % renewable energy systems have been done in Europe and agree that long-term electricity storage will be needed. Table 17.1 shows seasonal energy storage estimates there, which vary due to different assumptions about the renewable portfolio, whether nuclear, coal, or natural gas are used, the extent of the balancing area, grid connections, and backup capacity.

Table 17.1 Long-term storage for 80–100 % renewable energy systems (Droste-Frank 2015)

Region	Range (days)	Twh/year generated	Twh backup energy storage required
Germany 80 % renewable	1.7–5.8	500	2.3–8
Germany 100 % renewable	17.5–63	500	24–86
EU + North Africa + Mediterranean 100 % renewable	6–30	4900	80–402

These studies found that good connections at a continental-scale significantly reduced the need for long-term storage.

A study done for the state of California estimated that in a high-renewable electric grid, if wind and solar were unavailable for a week, 8 TWh of energy storage would be needed in California (CCST 2012).

Storage Goal: One Day of U.S. Electricity Power Generation

What would it take to provide the storage to supply all the electricity used in the lower 48 states for one full day? In 2013, the total electricity generated in the U.S. was 4058 TWh. So one day is 11.12 TWh. How might we do this? What are the most promising proven and yet to be proven tools in our energy storage toolbelt?

Pumped Hydro Storage (PHS)

Pumped hydro storage generates power by using electrically powered turbines to move water from a lower level at night uphill to a reservoir above. During daylight hours when electricity demand is higher, the water is released to flow back downhill to spin electrical turbines. Locations must have both high elevation and space for a reservoir above an existing body of water. Pumped hydro uses roughly 20–30 % more energy than it produces, with more electricity required to pump the water uphill than is generated when it goes downhill. Nonetheless, pumped hydro enables load shifting, and is important to balance wind and solar power.

Appearances can be deceiving: Pumped hydro is not a Rube Goldberg scheme. Many of you have used a kilowatt or two of pumped hydro yourself. PHS accounts for over 98 % of what little current energy storage exists in the United States, and is the only kind of commercial storage that can provide sustained power over 12 hours (typically, the other 12 hours are spent pumping the water up). Existing PHS facilities store terawatts of power annually, but account for less than 2 % of annual U.S. power generation. This isn't likely to increase much, since like hydroelectric dams, there are few places to put PHS. Only two have been built since 1995, for a grand total of 43 in the U.S., with most of the technically attractive sites already used (Hassenzahl 1981).

Existing PHS in the U.S. can store 22 GW, with the potential for another 34 GW more across 22 states, though high cost and environmental issues will prevent many from being built. Additionally, saltwater PHS could be built above the ocean along the West coast, but so far the high cost of doing so, shorter lifespan due to saltwater corrosion, distance from the grid, and concerns of salt seepage into the soil have prevented their development. Underground caverns and floating sea walls are other possibilities, but also aren't commercial yet.

PHS has a very low energy density. To store the energy contained in just one gallon of gasoline requires over 55,000 gallons to be pumped up the height of Hoover Dam, which is 726 feet high (CCST 2012).

In 2011, pumped hydro storage produced 23 TWh of electricity across the U.S. However, those plants consumed 29 TWh moving water uphill, a net loss of 6 TWh. So, how many PHS units would it take to give the U.S. that one day of electricity storage? Over 365 days, our 43 existing pumped hydro plants produced two days of energy storage (23 TWh). Thus, the U.S. would need more than 7800 additional plants (365/2 * 43). Rube Goldberg, I can imagine what you would make of this.

Compressed Air Energy Storage (CAES)

Besides pumped hydro, CAES is the only other commercially proven energy storage technology, and can provide up to a day of large-scale (over 100 MW) energy storage.

Using off-peak electricity, compressed air is pumped into very large underground cavities at a depth of 1650–4250 feet (Hovorka 2009), and then drawn out to spin turbines at peak demand periods. Typically, natural gas provides the power to compress and pump the air underground. When the compressed air is withdrawn, natural gas is used a second time to heat it and force it through expanders to power a generator. Current CAES facilities are essentially gas turbines that consume 40–60 % less gas than conventional turbines (SBC 2013).

But like pumped hydro, locations are scarce. There are only two CAES plants in the world: Alabama (110 MW) and Germany. The optimal site for CAES is a deep chamber within a salt dome which exist in only a few states (Fig. 17.5), since they're airtight, can handle frequent charging and discharging, with pure, thick salt walls that self-heal with air moisture, preventing leaks. This is not exactly run of the mill geology.

CAES has yet to be deployed in rock salt, aquifers, or abandoned rock mines because these formations are less likely to be airtight, and hence able to charge and discharge frequently and to maintain constant pressure. Underground areas once but no longer used to store natural gas or oil would have to be free of blockages that could gum up the works. Water is another limiting factor. High volumes are needed to cool the compressed air before storing it.

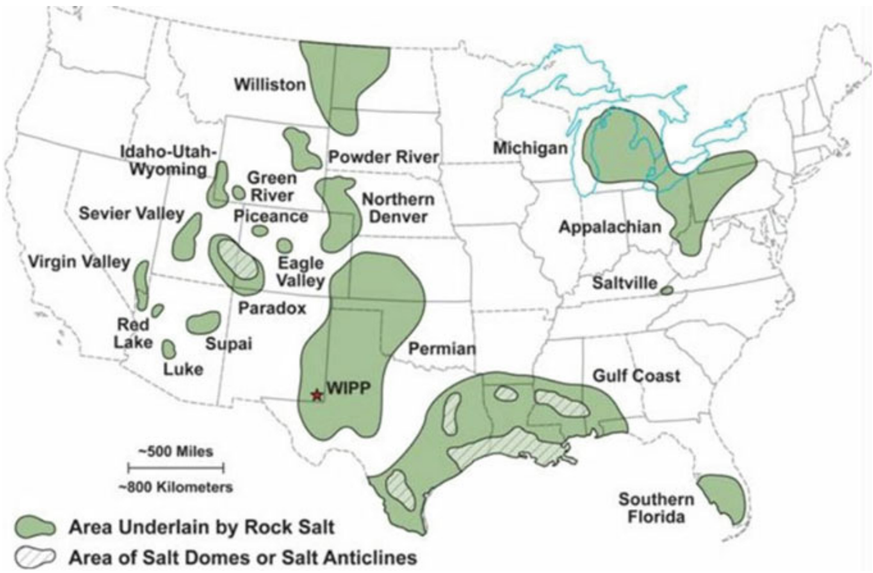


Fig. 17.5 Map of salt deposits in U.S. *Source* Hansen et al. (2011). Salt disposal of heat-generating nuclear waste. Sandia National Laboratories

Ideally, CAES would be combined with wind generation, but little commercial wind exists near potential CAES sites (Denholm 2013). One such $8 billion dollar project is in the planning stage in Utah. It would use the only known salt dome outside of Texas, Louisiana, or Alabama for a $1.5 billion dollar CAES to store electricity from a $4 billion wind farm in Wyoming to deliver power to Los Angeles over $2.6 billion of new transmission lines that run for 535 miles ($4.86 million/mile) (DATC 2014; Gruver 2014).

CAES systems generally have twice as much up-ramping capability as down-ramping. Translation: They can produce electricity faster than they can store it (IEA 2011a).

Based on nine vendor estimates, to build CAES units able to store one day of U.S. electricity would cost from $912 billion to $1.48 trillion. That's below ground. Above ground CAES would cost $3.8 trillion (DOE/EPRI 2013).

Concentrated Solar Power (CSP) with Thermal Energy Storage (TES)

You won't find a CSP plant on your neighbor's roof. CSP is a large power plant requiring considerable acreage—5.5 square miles for California's Ivanpah—where mirrors focus bounties of sunlight to boil water for steam generation. CSP contributes only 0.06 % of U.S. electricity. The United States has 1861 MW of CSP operating or under construction, mainly in California (64 %) and Arizona (24 %) because extremely dry areas with no humidity, haze, or pollutants are required.

Of the 1861 MW, only about one-quarter can also store electricity using thermal energy storage. Energy is stored as heat, usually in molten salt, with total CSP storage rated at 510 MW.

CSP is more capital expensive than any other power generation plant except nuclear. Eight plants cost a total of $9 billion (Solana, Genesis, Mojave, Ivanpah, Rice, Martin, Nevada solar 1, Crescent Dunes (NREL 2013).

Almost all CSP plants also have fossil backup to diminish night thermal losses, prevent molten salt from freezing, supplement low solar irradiance in the winter, and for fast starts in the morning. You can't hurry a sunrise.

CSP electricity generation in winter is significantly less than other seasons, even in the best range of latitudes between 15° and 35° (Fig. 17.4). To provide seasonal storage, CSP plants would need to use stone, which is much cheaper than molten salt. A 100 MW facility would need 5.1 million tons of rock taking up 2 million cubic meters (Welle 2010). Since stone is a poor heat conductor, the thick insulating walls required might make this unaffordable (IEA 2011b).

Nevada's 110 MW Crescent Dunes opened in 2015 with 10 hours of storage and is expected to provide an average of 0.001329 Twh a day. Multiply that by 8265 more Crescent Dune scale plants and presto, we'll have one day of U.S. electrical storage (11.12/0.001329 TWh).

Without storage, solar CSP and solar PV do nothing to keep the grid stable or meet the peak morning and late afternoon demand.

Hydrogen

This is a real contender. In terms of storage, hydrogen could do some heavy lifting.

Power-to-gas hydrogen is the only technology capable of compensating for several weeks of windless or cloudy conditions (SBC 2014). This process splits hydrogen from water with electrolysis and combines it with carbon from biogas to make methane. This method, and the methane it produces, is the best option for hydrogen storage, because there are few salt domes in which to store hydrogen, but there is already a natural gas (methane) pipeline, storage, and distribution infrastructure. However, power-to-gas is not commercial yet, and uses more energy to make methane than the energy in the methane, and is limited by the amount of biogas that can be generated (Andrews 2015).

Electrochemical Batteries

There are no commercially proven, utility-scale batteries that have been deployed. Those with a chance of debuting within the next 10 years are NaS (sodium–sulfur), advanced lead–acid (PbA), and lithium-ion. As with advanced auto batteries, there are challenges:

- Storing energy in a battery is no free lunch. Energy is lost due to heat and other inefficiencies. Roundtrip efficiency defines how much energy is lost in a "round trip" between the time the battery is charged and then discharged. Batteries lose 10–40 % of the energy generated due to roundtrip efficiency losses, so to produce 11 TWh would require generation of between 12.1 and 15.4 TWh to make up for losses (depending on the battery technology used).
- Lead–acid batteries take five times as long to recharge as to discharge.
- Battery lifespan is reduced if charged or discharged beyond optimal range.
- Li-ion are more expensive than PbA or NaS, can be charged and discharged only a discrete number of times, can fail or lose capacity if overheated, and the cost of preventing overheating is expensive. Lithium does not grow on trees. The amount of lithium needed for utility-scale storage is likely to deplete known resources (Vazquez et al. 2010).

Using data from the Department of Energy (DOE/EPRI 2013) energy storage handbook, I calculated that the cost of NaS batteries capable of storing 24 hours of electricity generation in the United States came to $40.77 trillion dollars, covered 923 square miles, and weighed in at a husky 450 million tons.

Sodium Sulfur (NaS) Battery Cost Calculation:
NaS Battery 100 MW. Total Plant Cost (TPC) $316,796,550. Energy Capacity @ rated depth-of-discharge 86.4 MWh. Size: 200,000 square feet. Weight: 7000,000 lbs, Battery replacement 15 years (DOE/EPRI p. 245).

128,700 NaS batteries needed for 1 day of storage = 11.12 TWh/0.0000864 TWh.

$40.77 trillion dollars every 15 years = 128,700 NaS * $316,796,550 TPC.

923 square miles = 200,000 square feet * 128,700 NaS batteries.

450 million short tons = 7,000,000 lbs * 128,700 batteries/2000 lbs.

Using similar logic and data from DOE/EPRI, Li-ion batteries would cost $11.9 trillion dollars, take up 345 square miles, and weigh 74 million tons. Lead–acid (advanced) would cost $8.3 trillion dollars, take up 217.5 square miles, and weigh 15.8 million tons.

These calculations exclude the roundtrip losses. It is even more expensive if you take roundtrip efficiency into account. NaS batteries have a roundtrip efficiency of 75 %. That means the U.S. would need to increase generation capacity by 33 % (1/0.75 − 1). So it's not just the cost that is prohibitive, we would need an insane amount of wind and solar to charge these goliath battery storage farms (Barnhart 2015).

Fig. 17.6 A 2 MW Li-ion energy storage system (DOE/EPRI 2013)

Siting utility-scale batteries in urban areas can be expensive. Anaheim estimated purchasing an acre of land to host 5 MW of batteries would cost $800,000 million to $2 million (Anaheim 2014). As you can see in Fig. 17.6, even 2 MW of Li-ion batteries take up quite a bit of land.

Battery Energy Storage at Grid Scale Is Limited by Materials

Mountain-sized amounts of materials, not metaphorically but literally, are required for utility-scale energy storage.

Barnhart et al. (2013) looked at how much material and energy it would take to make batteries that could store up to 12 hours of average daily world power demand, 25.3 TWh. Eighteen months of worldwide primary energy production would be needed to mine and manufacture these batteries, and material production limits were reached for many minerals even when energy storage devices got *all* of the world's production (with zinc, sodium, and sulfur being the exceptions). Annual production by mass would have to double for lead, triple for lithium, and go up by a factor of 10 or more for cobalt and vanadium, driving up prices. The best to worst in terms of material availability are CAES, NaS, ZnBr, PbA, PHS, Li-ion, and VRB (Barnhart et al. 2013).

Other Solutions

Less demand would help. That's you I'm talking to! Customers can use less power, insulate, and use distributed solutions such as combined heat and power (CHP), ice energy, private generators, and solar collectors. Everybody will need to do their part. Please turn out the lights when you leave.

It is not a slam dunk that vehicle-to-grid car batteries—an electric vehicle that pumps surplus power back into the grid—will ever be cheap or powerful or plentiful enough to provide grid services, helping to balance the grid, or that a smart grid will ever be clever enough to manage millions of EV/PHEV batteries. Also, some owners will opt out because this could shorten battery life (Kintner-Meyer et al. 2012; Palo Alto 2014). Nor can we count on the incomes of the bottom 90 % of workers growing enough to afford all electric cars.

Conclusion

Energy storage is required in order to replace other fuels, natural gas in particular, now used to create electricity and to balance the grid. Electricity from the grid is not a viable source for powering ships, trains, and trucks. For these purposes, electricity is unlikely to ever be a transportation fuel. But if push comes to shove, trucks could run on natural gas or small local trucks on electricity.

Energy cannot be stored for even a single whole day with current technology, yet weeks of storage are required to compensate for seasonal wind and solar.

When natural gas grows scarce, there is a risk that the demand for biomass to generate electricity, transportation fuel, fertilizer, and chemicals will be so great that whatever forests are left will be demolished. If Americans were to use their entire stock of hardwoods in forests to heat homes, our woodlands would be gone in four years (Hagens 2007).

The future grid will become increasingly fragile as fossil generation declines from 67 % of production today to a much smaller percent, as nuclear generation declines, and as intermittent wind and solar grow. The future grid will have more blackouts and struggle to provide electricity for all the essential services it supports today.

The grid will flicker out without energy storage. As far as the eye can see, the best hope rests on utility-scale batteries, since there aren't enough locations for (pumped) hydropower or CAES, but utility-scale batteries are far from commercial. Hydrogen remains an infant technology, not yet able to stand on its own.

Few people appreciate how limited the options will be once our premium abundant fossil fuels are gone—just when we need them to build very energy-intensive replacements.

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Chapter 18
Other Truck Stoppers: Mother Nature

My grandmother used to say “a stitch in time saves nine,” and this is especially true of neglected infrastructure. The American Society of Civil Engineers (ASCE) estimates that by 2020, U.S. roads, bridges, and transit will need $1.7 trillion in repairs and new infrastructure, but that only $877 billion will be spent, and this neglect will lead to a need for $6.7 trillion by 2040. Likewise, inland waterways and marine ports need $30 billion by 2020 but only $14 billion is likely to be spent, so by 2040 marine infrastructure will need $92 billion in maintenance and new construction (ASCE 2013).

The ASCE hasn’t included declining oil in their calculations, which will make it even costlier to repair and replace transportation infrastructure and vehicles.

If we are going to keep the country moving, we have to maintain this infrastructure. And we must gear up to deal with threats now over the horizon, but quickly approaching.

Crumbling Concrete

Roads are not rock, not made of granite. The lifetime of a road passes in the geological blink of an eye with the design life of asphalt and concrete pavement ranging from 10 to 20 years. Trucks crunch up asphalt in a decade or less. Even concrete cracks after being run over repeatedly by heavy trucks and exposed to freeze-thaw cycles. Cracks let in water and chemicals that rust rebar, which expands up to sevenfold, busting up the surrounding concrete (Courland 2011).

Roads are literally made out of oil. Asphalt, also known as bitumen, is a sticky, highly viscous liquid or semi-solid form of petroleum. Ninety-three percent of U.S. roads are paved with asphalt, because no other material has such strength and versatility.

Trucks may not stop running, but they will sure slow down as roads and bridges crumble.

Ships and barges will be affected too. Even concrete docks, piers, locks, and levees age and fail. The lifespan of concrete varies, but by and large, it falls short of

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the average life expectancy of a U.S. citizen. We mortals last longer than concrete. We're not mere mortar!

Rust and Corrosion

On the one hand, oxidation makes life possible for us carbon-based life forms. On the other hand, slow oxidation makes things rust. Anything made of iron or steel begins to rust as soon as it is fabricated. Trucks, trains and rails, ships, refineries, oil and gas pipelines, bridges, wind turbines, electric grid transmission towers, lines, and substations—all are under constant assault by rust. You can hold off rust, but it will cost you.

Corrosion is constantly chewing on energy infrastructure and eating into offshore platforms, pipelines, refineries, and drilling equipment. It is more expensive than all natural disasters combined, costing the U.S. $437 billion a year, 3 % of GDP.

Double hull ships, intended to prevent oil spills, are especially vulnerable to rust. This virulent phenomenon has been called a "supertanker plague," with new ships experiencing serious rust within just two years. Double hulls have accelerated rusting because corrosion has been inadvertently engineered right into the ship's design. The extra layer of steel gives rust more surface area to feed upon, much of it within inaccessible crawl spaces. This is one reason ships and oil tankers are retired after an average of 29 years. At that young age, they go to the scrapyard.

Climate Change

Everybody talks about the weather, but nobody does anything about it. Actually, that is not quite true. Transportation infrastructure has been designed to perform in many weather conditions. The design restraint is the weather that was foreseeable at the time of construction. Climate change once was unforeseen. A bridge that was built to withstand a hundred-year flood may experience such floods every 25 years as storms are thought likely to grow in frequency and severity from climate change. Or we may experience a storm not seen in 100 years every 25 years, as is occurring with Mississippi River floods.

As climate change shows its face, we can foresee sea level rise, severe hurricanes, storms and storm surge, and floods. The consequences may include:

- Submerged coastal oil refineries, nuclear, coal, and natural gas power plants. The Gulf, where many U.S. refineries are sited, is especially vulnerable because the land is subsiding as well.
- Washed out roads and rail tracks. More mud and landslides.
- Flooding of vulnerable coastal railways and subways that are underground, in tunnels, or below sea level.

- Loss of ports. If roads and rail near ports are lost due to rising sea levels, imports and exports will stop as ports become isolated islands.
- Loss of roads, rail beds, and bridge supports as their bases are eroded.
- Damaged oil, gas, water, and sewer pipelines.
- Shipping channels that are silted up after floods and severe storms, making them too shallow, damaging harbors, knocking out barge operations, and shortening the lifespan of roads.

Drought can stop freight in its tracks. Drought can lower rivers and strand barges. Drought reduces hydropower and thermal generation plants (fossil, nuclear) due to lack of cooling water. Drought reduces biofuel production.

In some regions, climate change will bring higher temperatures. Heat waves can expand and even buckle train rails, increasing derailments, soften and expand pavement that heavy trucks more readily turn into ruts and potholes, and stress bridges and roads by expanding their joints past design limits. Heat increases the loss of electricity over transmission lines at the same time as the demand for electricity to cool homes rises.

The Water-Energy-Transportation Nexus

"When we try to pick out anything by itself, we find it hitched to everything else in the Universe." John Muir's words apply to energy, transportation, and water.

Michael Webber at the University of Texas, Austin, points out that switching from petroleum fuels to alternatives such as biofuels, electric vehicles, hydrogen, or unconventional oil shifts our dependence from foreign oil to domestic water. This could more than double the water used in transportation from three percent now to seven percent in the future. The U.S. should make certain there is enough water to do this.

Traditional gasoline and diesel production uses two to five times less water than the production of oil shale, tight "fracked" oil, coal-to-liquids, gas-to-liquids, oil sands, electricity, and hydrogen.

Power plants use immense volumes of cooling water. So for each mile traveled, an electric vehicle charged with power off the U.S. grid can be twice as water-intensive as a car burning gasoline.

Talk about thirsty—you can't make ethanol from corn without a lot of water, about 1000 gallons of water for every gallon produced. If that water comes from rainfall, fine, but irrigation water is precious and needed by agriculture, fisheries, and drinking water. By miles traveled, gasoline consumes 2 gallons, while irrigated biofuels from corn or soybeans consume 20–100 or more gallons of water per mile traveled. As more biofuels are mandated, water consumption might go from one trillion gallons of water to make gasoline to a few trillion gallons of water, out of the total 36 trillion gallons the U.S. consumes.

Webber also said that “If energy sources become constrained or prohibitively expensive, then clean, piped water might also become constrained or prohibitively expensive in certain locations, or particular times of year. Consequently, ‘Peak Energy’ could trigger a decline in production of freshwater” (Senate 112-25 2011). You can’t pump water without energy.

Nuclear Power Plants

Nuclear power plants and waste containers will rust, corrode, crumble, and be attacked by rising sea levels. However angry the grandchildren are with us over using up fossil fuels so quickly, they will be even more upset if we don’t safely store the 140,000 tons of nuclear waste sitting at 121 military sites and 104 nuclear power plants while we still have the energy to do so (Alley et al. 2013).

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Chapter 19
U.S. Energy Policy: Oil Wars and Drill-Baby-Drill to Keep Autos Running?

Peak oil has been politicized. People who warn about it have been marginalized, denigrated as doomsters, called Chicken Little. At the time this book is being written, gasoline is cheaper than it has been in a decade. But the concept of peak oil really is just simple common sense: Sooner or later, the amount of oil coming out of the ground will begin to decline. You can argue about when, but not whether. When the time comes that world oil production begins its inexorable decline, the world will have reached peak oil.

U.S. energy security policy the past 30 years has consisted of increasing and diversifying sources of oil, creating the strategic petroleum reserve, relying on Saudi Arabia to balance oil markets and moderate prices, and a battery of conservation and efficiency measures. War, one after another, keeps the oil flowing, too. Domestic energy security is sought drilling in the deep waters of the Gulf, fracked tight oil, and in the future, drilling the Arctic.

Meanwhile, in 2008 the Great Recession hit, and to this day, most of the world economy remains slowed. This lowered pressure on oil supplies and led to lower oil prices (see Murphy and Hall 2011 for a model predicting this).

In 2005, the issue of peak oil became more widely known when Representative Roscoe Bartlett formed the House peak oil caucus to educate other representatives, and in 2005 Robert Hirsch wrote a peak oil mitigation plan for the Department of Energy.

In 2006, Frank Verrastro, now with the Center for Strategic and International Studies, warned at a U.S. Senate hearing, “We cannot ignore preparations for transitioning to the inevitable post-oil world. To do so requires a political will on the part of both the U.S. consumer and the government. To date, despite higher energy prices, real and threatened interruptions in supply, environmental damage, hurricanes and blackouts, that critical ingredient remains lacking. This means that the U.S. energy future likely will be shaped, at least in part, by events outside of our control and beyond our influence. Calls for energy independence, absent major technological breakthroughs and a national commitment, ring hollow, and in the near term are both unrealistic and unachievable” (Senate 109-412 2006).

In 2007, the Government Accountability Office recommended the Secretary of Energy take the lead in coordinating federal agencies to launch a peak oil strategy, including a good estimate of the timing of peak oil production and advice to Congress about measures to mitigate the consequences of a peak.

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In 2009, then Senator John Kerry of Massachusetts summed up U.S. energy policy: “Ever since President Nixon set a goal of energy independence by 1980, price spikes and moments of crisis have inspired grand plans and Manhattan projects for energy independence, but the political will to take decisive action dissipated after each crisis passed. That is how steps forward have been reversed and efforts have stood still even as the problem has gotten worse. In 1979, President Carter asked ‘Why have we not been able to get together as a nation and resolve our serious energy problem?’ And regrettably, despite the strong efforts and courage of President Carter to tell the truth to Americans about energy and set America on the right path in the 1970s, we are still struggling to meet the same challenge” (Senate 111-78 2009).

Former President Carter also spoke at this same 2009 hearing, describing how, when he came to office in 1977, the average car got 12 miles per gallon (mpg), and was mandated to be 27.5 mpg within eight years. “But President Reagan and others didn’t think that was important,” said Carter. “We have gone back to gas guzzlers, which may be the main reason Ford, Chrysler, and General Motors are in so much trouble. Instead of making efficient automobiles, they made the ones which made more profit. Of course, the oil and automobile companies have always been in partnership, because the oil companies want to sell as much oil as possible, and the automobile companies make more profit on gas guzzlers. So, there was kind of a subterranean agreement there.”

Carter said the president has a responsibility to educate the American public about energy, like he did over his four years in office. Memorably, one of his speeches began: “Tonight I want to have an unpleasant talk with you about a problem unprecedented in our history. With the exception of preventing war, this is the greatest challenge our country will face during our lifetimes. The energy crisis has not yet overwhelmed us, but it will if we do not act quickly. It is a problem we will not solve in the next few years, and it is likely to get progressively worse through the rest of this century. We must not be selfish or timid if we hope to have a decent world for our children and grandchildren. We simply must balance our demand for energy with our rapidly shrinking resources. By acting now, we can control our future instead of letting the future control us” (Carter 1977).

This was unpleasant dinner conversation. President Carter was not invited back to serve a second term.

For a number of reasons, national elected officials are not likely to educate the public about the coming energy crisis. Some even fear it would cause a stock market crash. A candidate bearing bad news and prescribing solutions that require sacrifice will lose the next election to anyone offering easy to swallow bromides and promising a happy, renewable future (Friedemann 2011). Remember Jimmy Carter.

Cars and Light Trucks Are a Huge Part of the Problem, Using 63 Percent of Transportation Oil

Our descendants will be flabbergasted, or more likely angry, when they learn the Oil Age ended sooner than necessary because billions of barrels of gasoline were wasted on low-mileage 4000 pound cars and light trucks that usually carried just one passenger, that fuel economy wasn't even considered in most purchase decisions, and that even though efficient cars were available, we didn't buy them. They will remember us as oil gluttons (Turrentine 2005).

As U.S. House Representative Sherwood Boehlert of New York said in 2005, "Our nation is ever more dependent, stunningly dependent on the world's most unstable region for the energy that is the lifeblood of our economy. We cannot reduce our oil consumption meaningfully unless we address transportation. Our nation's fuel economy is worse than it was 15 years ago. That ought to be unacceptable, intolerable. I want everyone to remember the costs of inaction: they can be measured in dollars, particularly in the funds we spend on the military and homeland security, and in lives" (House 109-3 2005).

What happened decades ago, in the 1970s should have been a national wake-up call. Briefly, we did arise from our slumbers. In the late 1970s, the Organization of Petroleum Exporting Countries (OPEC) deployed "the oil weapon," placing an embargo on the export of its oil in retaliation for America's support for Israel. Gas supplies were so tight that President Richard Nixon imposed rationing across the country; vehicles with license plates having an odd number as the last digit could buy gas on odd-numbered days of the month, while others could buy only on even-numbered days. A Republican rationing gasoline! Realizing that cars getting 12 miles per gallon are a recipe for national disaster, in the late 1970s President Jimmy Carter implemented the first nationwide fuel efficiency standards for cars and light trucks. Gas guzzlers were recognized as a national security threat under these new Corporate Average Fuel Economy (CAFE) regulations.

We could have gone a long way with this idea, but we lost our way. In 1986, Ronald Reagan rolled back CAFE standards causing America, in that year, to double oil imports from the Persian Gulf nations and to burn more oil than is in the Arctic National Wildlife Refuge.

Across all classes of vehicles, from cars to large trucks, miles per gallon went from 11.9 mpg in 1973 to 16.9 mpg in 1991 and then barely rose for 22 years to 17.6 mpg in 2013, with light trucks improving the least, from 17 mpg in 1991 to only 17.2 in 2013 (Sivak et al. 2015). Worse yet, light trucks and SUVs were exempted from gas mileage goals, and a tax benefit for drivers who use vehicles for work could write off a 10 mpg, 38 thousand dollar Hummer on their tax returns. In 2003 this benefit was expanded to $100,000 (Barlett et al. 2003).

From the time of the initial CAFE legislation, 32 years elapsed before we got back on course. In 2007, federal legislation upped the fuel efficiency requirements, and in 2012, President Barak Obama finalized an agreement with 13 large automakers to increase fuel economy to 54.5 miles per gallon for cars and light-duty trucks by model year 2025.

For too long, we've being going in the wrong direction. Every time the price of gasoline goes down, Americans buy more SUVs and trucks than efficient cars. Since September 2014, when gas prices began to fall, the average miles per gallon dropped from 25.8 to 25.4 today, with a record breaking 3.1 trillion miles driven because of the cheaper gas.

If the public knew about the energy crisis, would they stop buying gas hogs? In 2014, Californians knew the state was in the most serious drought in memory (1200 years in fact), but when cutbacks were voluntary, reduction goals were not met. The price of water was raised, and only then was water use cut in California.

The same type of price incentive is probably required for more fuel-efficient cars and light trucks, so the less efficient a car or light-duty truck is, the more it should be taxed. Gas taxes should be significantly increased to induce Americans to purchase fuel-efficient cars. Even when gas prices are low, these higher taxes would be an incentive to drive fuel-efficient vehicles, and to drive less. This tax revenue also could help pay to fix America's roads and bridges. Alas, in that a substantial number of politicians are against taxation, there is little chance of a more fuel-efficient car fleet being in place when energy shortages strike. There's not a lot of courage required for a politician to oppose gas taxes. Their credo: "Ask not what you can do for your country. Ask what your country can do for you!"

Energy Policy: Cars

Cars are the least necessary and the most inefficient mode of transportation other than aircraft.

Yet, it appears that the American Car is Sacrosanct, the very essence of what former President George H.W. Bush meant when, in 1992, he said "the American Way of Life is Not Negotiable."

Not everyone agrees. Senator Richard Lugar of Indiana once asked why, regardless of presidential leadership, the American public continues to buy cars and trucks that use a lot of oil. Lugar said this continued despite the fact that many Americans believed we invaded Iraq so we could continue to run SUVs and have all the pleasures to which we've become accustomed. Why, he wondered, haven't we ever said, "We've had enough, our dependence upon foreign oil has really got to stop" (Senate 111-78 2009).

In terms of moving the needle on car gasoline use, the Congress and the U.S. Department of Energy have focused much of their effort on ethanol production. In theory, adding ethanol to gasoline could reduce gasoline use. In fact, as much fossil energy goes into making ethanol as it contains. Corn ethanol farming also accelerates topsoil erosion, underground and irrigation water depletion. As a strategy to cut gasoline use, corn ethanol has backfired on us.

Electric vehicles are a long way from becoming widely adopted, as are natural gas or hydrogen cars. Proposals for flex cars that burn several kinds of fuel didn't go far because auto makers pointed out these vehicles would be very inefficient since a car can't be optimally tuned for all fuels (though there are 12 million cars that can burn gasoline or E85).

So here we are, 42 years after the first U.S. oil crisis of 1973, far more dependent on oil, and with 108.2 million more Americans consuming it, two-thirds of them living in far-flung suburban sprawl and rural areas. More than any other nation, the non-negotiable American way of life has evolved to be dependent on oil and four million miles of roads to get to distant suburbs, jobs, and shopping malls.

Wars Keep the Oil Flowing

In a 1980 "State of the Union" address, President Carter stated that due to "the overwhelming dependence of the Western democracies on oil supplies from the Middle East…[any] attempt by an outside force to gain control of the Persian Gulf region will be regarded as an assault on the vital interests of the United States of America, and such an assault will be repelled by any means necessary, including military force."

Since then we've invaded, occupied, or bombed Iran (1980, 1987–1988); Libya (1981, 1986, 1989, 2011); Lebanon (1983); Kuwait (1991); Iraq (1991–2011, 2014–present); Somalia (1992–1993, 2007-present); Saudi Arabia (1991, 1996); Afghanistan (1998, 2001–present); Sudan (1998); Yemen (2000; 2002-present); Pakistan (2004-present); and now Syria.

One of America's energy security strategies has been war. But it would be self-defeating to spend the remaining oil fighting wars over oil, especially with the risk of escalation into a nuclear war. This could cause over a billion people across the world to die in the resulting nuclear winter and radiation from ozone loss over the following ten years (Mills 2008).

In 2012 testimony before the U.S. House of Representatives, Mike Breen of the Truman National Security Project described a nation and planet that has become an oil junkie. Said Breen, "Our dependence on oil as a single source of transportation fuel poses a clear national security threat to the nation. As things now stand, our modern military cannot operate without access to vast quantities of oil. Our economy is equally dependent, with over 95 % of our transportation sector reliant on oil. This lack of alternatives means that oil has ceased to be a mere commodity. Oil is a vital strategic commodity, a substance without which our national security and prosperity cannot be sustained. The United States has no choice but to do whatever it takes in order to obtain a sufficient supply of oil. We share that sad and dangerous predicament with virtually every other nation on earth" (House 112-159 2012).

Retired Air Force General Charles Wald testified at a Senate hearing in 2007 that many believed the U.S. military is solely responsible for energy security, what he calls the "Dial 1-800-The-U.S.- Military" syndrome, since people assume the U.S. military is a "toll-free" resource, and that "energy security can be achieved solely by military means-we need to change this paradigm because the U.S. military is not the best instrument for confronting all the strategic dangers meaning from oil dependence". He was dismayed when global oil company executives thanked him for providing worldwide security to ensure the free flow of oil—with no assistance from other nations—because Wald does not believe the U.S. military can or should "be everywhere to protect all the vulnerable components of the global oil infrastructure". Instead he recommends increasing transportation efficiency as the single most important step America could take, and deplores America's light-duty vehicles for having the worst average fuel efficiency in the developed world (Senate 110-6 2007).

What if we can't get our fix of oil? What would happen?

Vice Admiral Dennis McGinn described a scenario of how war might erupt. First, climate change would trigger a long chain of disasters. Across the planet, nations would experience drought, floods, disease, crop failures, sea level rise, ocean acidification, and wildfires. The resulting instability would result in hunger, failed governments, and migrating populations. Turmoil would ensue, which would create fertile breeding ground for organized crime, paramilitaries, extremists, and terrorism. The U.S. military would be called in.

At the same time, resource wars would erupt in the most volatile regions of the world, especially over oil, as continued population growth over the next 20 years widens the gap between oil supply and demand. All the while, U.S. fossil fuel dependence will continue.

Admiral McGinn concluded that in a global outbreak of wars over dwindling oil supplies, our military would be stretched too thin to protect the free flow of oil in hostile regions. The suffering, the turmoil, the lost lives, the cost of war—this presents an unacceptable risk to the nation, said the admiral. (House 111-20 2010)

Welcome to the doomster club, Admiral McGinn. What a bunch of killjoys! They would have you believe that America's longstanding "campaign for energy independence" has a way to go.

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Chapter 20
Where Are We Headed?

We have been living like gods. Our task now is to learn how to live like humans. Our descent will not be easy—Randy Udall (Senate S6373 2013).

You can bet your lifestyle on this: We are facing a transportation fuel crisis.

There is a bottom to every well. As world population rises, more people will need oil, and they aren't making any more of it. Biofuels, batteries, and electricity from windmills, solar, geothermal, and nuclear power plants won't keep trucks, tractors, locomotives, and ships running.

Hubbert's Curve is More Like a Cliff

We were warned. In the 1950s, geoscientist Dr. M. King Hubbert plotted a graph that tracked the historic rate of ascent of world oil production, a peak, and the downward slope of remaining annual world oil production. At some point, we will have used half of all the recoverable oil that ever existed on our planet. That is Hubbert's peak.

When I first saw Hubbert's bell curve of oil production, it didn't seem all that dire. In 2030, there would be as much oil as 1980. Society could cope with that for many decades.

But that was before I understood that much of the remaining oil after peak production was thick, tarry stuff, not the easy, free-flowing oil (like good old sweet Texas crude) from earlier times. These remaining dregs require a lot of energy in secondary and tertiary recovery methods, and are often not near existing oil pipelines, so even more energy is required to transport it with (new) rail or roads to refineries. This extra energy—the dark part of the curve in Fig. 20.1—subtracts from the net energy available to fuel industrial civilization (the light area), to the point where the energy left available to society appears to go off a cliff. The Intergovernmental Panel on Climate Change (IPCC) projections, which predicts endlessly rising fossil production until 2100, fail to account for the quality of oil that remains, for oil that will be stranded and never used because of its distance from infrastructure and the energy cost to claim it. Many energy researchers—Heinberg,

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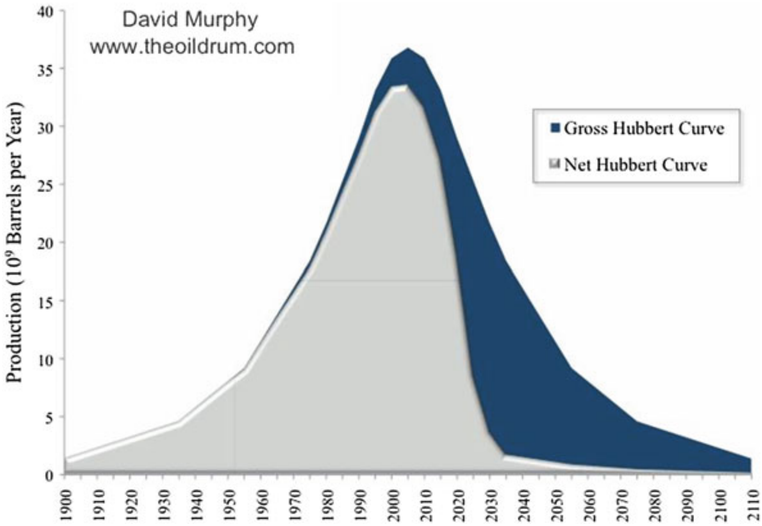

Fig. 20.1 Gross (*dark*) and Net (*light*) Hubbert Curves. *Source* Murphy, D. June 22, 2009. The Net Hubbert Curve: What Does It Mean? The Oil Drum

Höök, Rutledge, and Patzek among them—say the IPCC relies on reserve estimates that have been inflated and are outdated (Heinberg et al. 2010; Höök et al. 2010; Rutledge 2014; Patzek et al. 2010).

The "good news" is that greenhouse gases will begin to decline after peak oil production. That won't save us from climate change, which is locked in, and will wreak havoc for generations to come. But be thankful that like fossil fuel supplies, our ability to pump greenhouse gases into the air is finite.

Once the oil flow rate declines, formerly recoverable oil, coal, and natural gas reserves will increasingly revert back to being unobtainable resources. Eventually, the energy and money required will flat out exceed the value of exploiting these reserves. Geographically and geologically disadvantaged, these fossil fuels will be stranded in place. This problem is not unheard of: We know there is a lot of platinum on many asteroids. And yet we know that because of the cost of bringing it home, far away and out of reach is where this platinum will remain.

So who is right about the peak of the Oil Age? Rather than spin our wheels debating that date, focus on this certainty: You can argue about when, but not whether, world oil production will peak and decline.

This much is not in dispute: The U.S. is not prepared for declining oil, let alone a steep decline rate. Collectively, we are blindly captive to a free market economic religion, which preaches that there are no limits to growth. All you have to do is throw enough money and human ingenuity at a problem … and the magic of the market will fetch the resource or a substitute. Can that be true? Do we want to bet our lifestyles on that? The previous chapters have examined the existing possibilities and found them wanting.

Setting National Priorities for How Petroleum Is Used

We have low hanging fruit in America, a bountiful harvest of easily reached ways to change how we use transportation fuels. Even when oil shortages occur, in that 63 % of American oil is consumed by autos, vans, pickups, and sport utility vehicles, a great deal of fuel can be saved and shifted to trucks, trains, and ships. Yes, we want cars in our two-car garages. But we also want the cornucopia of goods that fill our homes and stores. Driving fewer miles in more fuel-efficient cars, more and better mass transit, sharing cars, biking, walking, and trucks modified to run on compressed and liquefied natural gas (if natural gas lasts longer than oil)—like it or not, that is just the beginning of what we will need to do.

Very few nations are as wealthy as America, and in many countries oil is neither abundant nor affordable. Auto fuel is higher-taxed and much more expensive across Europe. In turn, they drive much more fuel-efficient cars, and used the tax revenue to build mass transit that is the envy of many American tourists. Europe has coped. In Lima, Peru, nearly all cars double as taxis. In an instant, cars are transformed into taxis simply by slapping a plastic taxi symbol on their roofs. Many vans travel main roads with destination signs in the window. Buses at depots don't depart until completely full. In the Peruvian countryside, people pile into and travel on open flat-bed trucks and empty railcars. We call this the Third World. They do it without cell phone apps. Ironically, in America, we view Uber and the emerging "sharing economy" (Airbnb, for example) as futuristic high-tech. Thanks Lima for showing us the way.

Across the board, petroleum needs to be saved, including the 14 % of oil used in the U.S. for non-transportation needs in industry, electricity generation, and heating.

Air freight is up to 600 times less efficient than large cargo ships, so air freight has to go. Do you absolutely, positively have to have it overnight? Save air freight for vital needs.

Since ships are by far the most efficient means of moving goods and also happen to burn the cheapest dregs of crude oil, we should use them whenever possible. As transportation fuels become more precious, many port cities along coasts, rivers, and lakes will gradually resume the leading roles they played several centuries ago. For that to happen, the U.S. must maintain, upgrade, and replace aging locks, docks, and ports. The U.S. should no longer neglect its domestic waterway transportation infrastructure and corridors along rivers, lakes, and coasts. They are falling apart (NRC 2015; AASHTO 2013). Now is the time to dredge harbors, fix piers, and alter locks so they won't need electricity nor fossil fuels to open and shut, and in anticipation of rising sea levels. We Americans should live up to our self-image, and be ambitious—a network of new canals would make life easier for our grandchildren.

Food Distribution: Putting Food on the Table

Because there have been so few problems with the food supply system in America, few cities or states have planned for disruptions that cause a prolonged crisis. Climate change will alter rainfall patterns, and deplete underground water supplies (Konikow 2013). But here we'll focus on energy, and how we use it to move food from farm to market.

Food travels extraordinary distances. Over 80 percent of U.S. food calories (wheat, corn, soy, cattle, hogs, etc.,) are grown in the interior U.S. states. Yet by 2050, 80 % of 400-plus million people in the U.S. are expected to be living within 200 miles of the coast, far from our food.

We need to move as much of this food as possible by rail, and not by truck. Today, trucks play an overweight role in moving food from farm to market. Unlike the roads that trucks travel, rail is not maintained nor expanded by public tax dollars. The nation has seven major, class one rail companies, and about 500 short-line rail companies. These short lines are particularly critical in providing a rail bridge from farming regions to major rail lines. Because they are cash-starved, they are in growing disrepair. This is a tragedy that will hit us in the gut, at the family dinner table. As with highways, rail should be funded by the public with tax dollars, especially short-line rail. We certainly need more short-line rail in the corn and wheat belts to move food energy efficiently.

Necessity is often the mother of invention. During World War II, "victory gardens" bloomed across America. Something similar, though very different, is happening today. Though not primarily motivated by worries over energy, a growing movement to consume more locally grown foods has arisen across the country. "Locavores" and their "slow food" movement are fostering the growth of locally grown, healthy, fresh food using sustainable farming practices. This movement rejects industrial farming and is reliance on Godzilla-sized tractors that plant and harvest monoculture crops grown using natural-gas-based fertilizers and oil-based pesticides, and in which food is moved thousands of miles between the inland and coastal areas. Happily, this coincides with the need to minimize the use of transportation fuels. A caveat: Small quarter-filled local trucks bringing food into farmer's markets can use more energy than large semis filled with food from many hundreds of miles away (Hamilton et al. 2013).

The transportation fuels that move grains, fruit, vegetables, and meat cross-country won't always be so cheap and available. Remarkably, the local food movement erases many political and cultural divisions. Democrat or Republican, red state or blue, we all eat, and we all take pride of place in what is local.

To reduce the trillions of miles driven by suburban and rural dwellers, perhaps these regions will evolve to be more like Provence, France, where small businesses and farms make cheese, beer, and wine or grow high quality fruit, nuts, and other crops for transport to the nearest cities. In fact, in pockets across the country, that is exactly what the local movement is producing.

Isaac Asimov and Admiral Hyman Rickover on Energy Descent

Many who have come before realized the Oil Age was not permanent. Many have wondered how long it would last, how we would deal with this change, and have left their thoughts behind for posterity to consider. To my mind, Isaac Asimov and Admiral Hyman Rickover were particularly profound. Famous for their span of knowledge and ability to see the future, they are muses. With apologies to both, I have condensed below the troubles that they foresaw.

Isaac Asimov, "the Future of Humanity," 1974

In 1933, I read a story called "The Man Who Awoke" by Lawrence Manning. In it, the hero wished to see what the world of the future would be like. So he invented a potion, which when he drank it, put him to sleep for 5000 years. When he awoke, he thought he was going to come out and see a very futuristic world with all kinds of extremely super-modernistic devices flying through the air, and magical food pills and all that. And instead, what did he find? He found a very constricted world. A world in which everybody lived rather not very lavish lives, dressed in homespun, and they walked everywhere, and they worried a lot about what the next meal would be. And so he said to them "What is this? You guys are leading such constricted lives. Where's all this futurism I expected?" So they said, "Oh well, you don't understand. We're short on energy. Very short on energy because some thousands of years ago there was a generation or two of human beings who burnt up all the coal and oil on Earth, and left nothing for us." And our hero said, "Strange you should say that. I happen to be from the very generation that did this to you!" And so they tried to lynch him, naturally. And he got back to the vault just in time, slammed the door, and took another potion to see if anything new happened 5000 years later still.

When I was 13, I started thinking major premise: The Earth's volume is finite. Minor premise: The total volume of coal and oil on the Earth is less than the total volume of the Earth. Conclusion: The volume of coal and oil are finite. You would think that this was so obvious! Well, here we are. The world as a whole has eaten better, has lived better, and has had a higher standard of living than it has ever had before. And we haven't really appreciated how temporary this is. There is no need to decide whether to stop the population increase or not. There is no need to decide whether the population will be lowered or not. It will, it will!

The only thing mankind has to decide is whether to let population decline be done in the old inhumane method that nature has always used, or to invent a new humane method of our own. If we do try to keep the birth rate down, we're going to have to give women interesting things to do. We're going to have women help in running the government, and science, and industry, whatever there is to run in the *twenty first century. In short, the twenty first century, if we survive, will be a kind of women's lib world.*

That is the only choice that faces us; whether to lower the population catastrophically by a raised death rate, or to lower it humanely by a lowered birth rate. And we all make the choice. And I have a suspicion that we won't make the right choice, which is the tragedy of humanity right now. I've been so shrewd that I fixed it so that I was born in 1920. Which means I'll be safely dead. Before the crunch comes!

But you guys will see for yourself. I hope you see a world in which mankind has decided to be sane. But I must say in all honesty that I figure that the chances are against it (Asimov 1974).

Admiral Hyman Rickover, "Energy Resources and Our Future," 1957

Fossil fuels resemble capital in the bank. A responsible parent will use his capital sparingly in order to pass as much as possible of his inheritance on to his children. A selfish and irresponsible parent will squander it in riotous living and care not one whit how his offspring will fare.

It seems sensible to me to take a long view, even if this involves facing unpleasant facts.

For it is an unpleasant fact that according to our best estimates, total fossil fuel reserves recoverable are likely to run out at some time between the years 2000 and 2050. For more than 100 years we have stoked ever growing numbers of machines with coal; for 50 years we have pumped gas and oil into our factories, cars, trucks, tractors, ships, planes, and homes without giving a thought to the future.

Occasionally, the voice of a Cassandra has been raised only to be quickly silenced when a lucky discovery revised estimates of our oil reserves upward, or a new coalfield was found in some remote spot. Fewer such lucky discoveries can be expected in the future, especially in industrialized countries where extensive mapping of resources has been done. Yet, the popularizers of scientific news would have us believe that there is no cause for anxiety, that reserves will last thousands of years, and that before they run out science will have produced miracles. Our past history and security have given us the sentimental belief that the things we fear will never really happen—that everything turns out right in the end. Prudent men will reject these tranquilizers and prefer to face the facts so that they can plan intelligently. Can we feel certain that when economically recoverable fossil fuels are gone science will have learned how to maintain a high standard of living on renewable energy sources?

War, of course, cancels all man's expectations. I suggest that this is a good time to think soberly about our responsibilities to our descendants—those who will ring out the Fossil Fuel Age (Rickover 1957).

More Research on How to Get the Most Bang for the Energy Buck

Thinking about the future should be sobering, and still we must do it. Yet, it was hard to find government or think tank research on reducing energy demand in transportation. Most future scenarios assume endless growth, worry about the costs of widening roads to reduce congestion and where to construct new roads. Projects are assessed based on cost, not energy reduction. When energy is mentioned, it is nearly always concerned with how much greenhouse gas would be reduced, not how to reduce energy demands.

Magical thinking that scientists will come up with something, that America has a century of energy independence, that there's no urgent need to reduce oil consumption—that's what we are counting on. We've invested trillions of dollars in our transportation infrastructure, and see no pressing need to make it ready for the road ahead, a time when there will be less oil.

We should go into the future with our eyes wide open. We have no choice but to assess how much energy goes into all the things we take for granted. That includes our food, our vehicles, and how we go about moving goods around the planet like gods.

Science can help. In 1975, the field of net energy began to be developed at Stanford University (Connolly et al. 1975). The idea is that something that produces energy—ethanol, photovoltaics, wind mills, coal-fired power plants, nuclear power—also uses energy in their creation, maintenance, and decommissioning to create those kilowatts. Since 1975, the field has slowly developed around an idea called Energy Return on Investment (Hall and Cleveland 1981; Hall et al. 1981; Cleveland and Hall 1984; Murphy and Hall 2010, 2011; Hall 2011; Hall et al. 2014; Guilford et al. 2011). EROI is the ratio of the energy delivered by a process to the energy used directly and indirectly in that process.

Ethanol shows the value of doing an EROI analysis. When you take into account the energy used in dozens of steps, such as to create fertilizers, to plant and irrigate a corn field, to harvest the corn, refine it into ethanol, and move it to service stations, the net energy that goes into American gas tanks is less than what was put into the process (Murphy et al. 2011b).

EROI analysis makes it possible for society and policy makers to investigate our options and make the best energy choices. Tad Patzek, former professor of civil and environmental engineering at Lawrence Berkeley National Laboratory (LBNL), proposed a broad EROI study of a range of energy sources in 2006. But he was unable to get funding "to compare BTU's to BTU's for apple to apple comparisons and consistent thermodynamic descriptions of all major energy capture schemes." He concluded that this might be due to "no one wanting to know they may be working on a senseless project, such as industrial hydrogen from algae."

No doubt there is some truth in what Patzek said. There is also a fundamental problem with EROI. It is called the boundary issue. What do you include in a calculation, and what do exclude as outside the process? In the case of ethanol, do you include the energy needed to make the tractor? In the case of a concentrated solar power plant out in the desert, do you include new roads that have to be built? Do you include the energy necessary to support workers' paychecks?

Forty years later after laying the groundwork for the field, in April 2015, Stanford hosted a conference bringing the best minds in the field together, and attempting to seed interest in creating a Net Energy Institute. Since it is energy, not money, that fuels society, net energy should become a standard policy tool (Schwartz 2014). Most of those attending agreed on that much.

To some observers—I was among them—the conference came up short because it failed to make headway on the boundary issue. What was apparent is that different interests want to define boundaries either more narrowly, or more broadly. For advocates of ethanol, you don't want to include the tractor, and if you are selling solar in the desert, you aren't going to want to include the road. When "science" is not objective but advocative, differences will be magnified. It was apparent, at least to my thinking, that agreement on boundaries will be very difficult to reach.

Nonetheless, the energy research community must try. The starting point is transparency, and agreement that no EROI is worth its salt unless the boundaries of what is included and what is excluded are explicitly disclosed and spelled out, as in Murphy and Hall's 2011 "Order from Chaos: A preliminary protocol for determining the EROI of Fuels" (Murphy et al. 2011a). Absent this kind of net energy assessment, the critical decisions ahead will be made by the blind leading the blind. We'll waste away building Rube Goldberg contraptions that steal rather than deliver energy.

Shouting into the Wind

In my world, it is not morning in America. It's later in the day than that.

I was a systems analyst for a global shipping company that operated in more than two dozen countries. Every day, I was reminded of this manifest truth: Everything in our homes, everything in our stores, got there on a truck at some point. Before that, many of those goods also were transported by ship and/or train.

A "shipping company" is not just ships. Using trucks and trains, goods and freight move to the ports where they are loaded onto container ships. These ships—many four football fields in length—carry up to 18,000 twenty-foot containers. In our case, they departed Asia with finished goods and crossed the Pacific Ocean to U.S. West coast ports where containers were loaded onto trains and trucks and moved to their destinations. On the return voyage, ships crossed the Pacific up to 60 % empty, a huge waste of fuel (Fuller 2006).

In order to do my job as systems analyst, I had to understand the business from top to bottom. What I came to understand is that first and foremost, in order to compete against other shippers, we had to be the most efficient transporter of freight.

In a sense, this book really is about the "shipping business," but on a much grander scaler, where America, the world, and civilization itself are both the shipper and the recipient. The challenges are the same. Make sure there are no system-level problems that can slow or stop the movement of goods and freight. Look ahead and identify opportunities to move things with the thriftiest use of resources.

The systems analyst in me is shouting out to anyone who will listen: We are headed toward a day not too far away when the system as we know it will break down. We will not have enough transportation fuel to sustain our way of life.

Denial is not a strategy. We have options and opportunities. But we must act fast —with foreseeable energy, electricity, and climate change crises on the horizon, there is no time to lose. Seize the moment.

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