Energy Production: Present and Future

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Abstract

This paper examines several proposed energy production methods for their economic and environmental potential. The best areas for public investment in research and development are identified as wave energy, enhanced geothermal systems, concentrated photovoltaics, and industrial carbon capture and sequestration. The importance of public research and development in overall energy policy is emphasized.

Contents

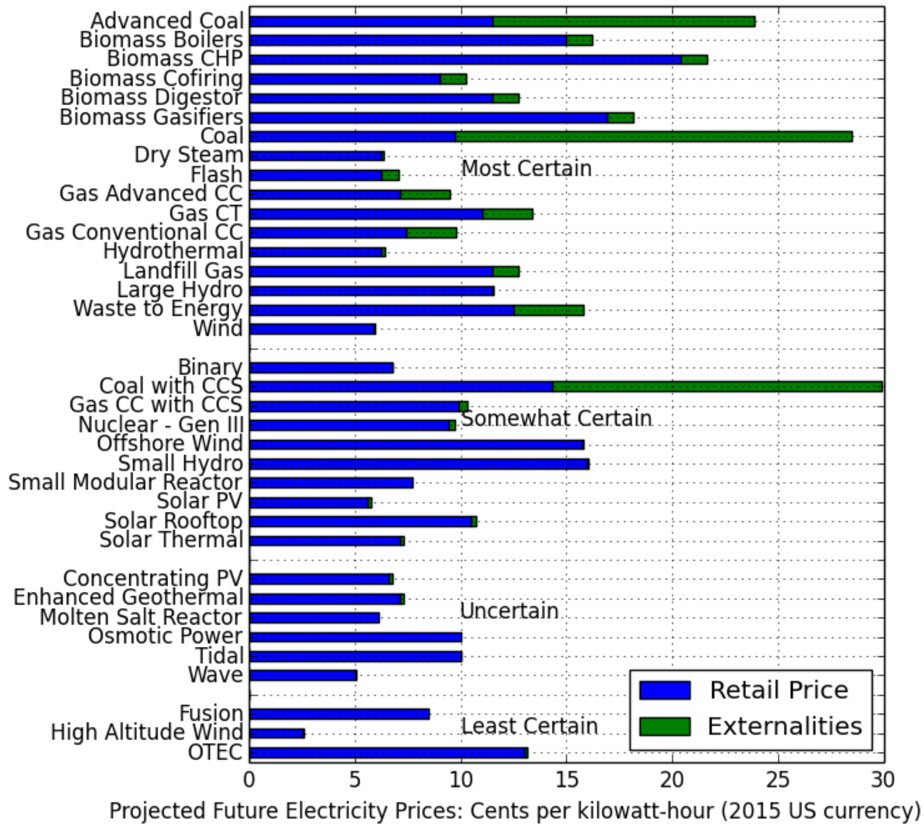
Introduction

Energy is the lifeblood of the modern economy. Every aspect of our lives, including our meals, travel, communication, homes, and manufactured goods, requires access to reliable, abundant, and affordable energy. Today the vast majority of that energy comes from fossil fuels: coal, oil, and natural gas. Despite the tremendous prosperity enabled by the refining and combustion of fossil fuels, these technologies all come with troubling costs: damage to the human health from air pollution, the spoliation of natural areas through mining and drilling, and the dangerous climate changes that result from the release of carbon dioxide (CO_2) into the atmosphere.

In the 21st century, the world's demand for energy will continue to increase. The U. S. Energy Information Administration predicts an increase of 56% just between 2010 to 2040 [33]. Continued heavy reliance on fossil fuels will result in mounting health and environmental costs. Furthermore, while the world does not seem to be in any imminent danger of running out of coal, oil, or gas, over-reliance on these resources will strain supplies and result in higher prices, placing a drag on the world's economy. Prices on all three are likely to generally increase through 2035 [27]. There is thus an urgent and critical need to develop alternative sources of energy.

Unfortunately, as we will show, no alternative technology at today's level has the potential to result in the wholesale replacement of fossil fuels. Biomass and biofuels are too expensive, and each comes with its own sets of environmental problems. Nuclear power is effective and clean, yet unattractive to investors, due to high capital costs and negative public perceptions. Wind and solar power remain expensive, and their deployment is limited by the ability of an electric grid to handle intermittency. Other energy sources-wave power, enhanced geothermal systems, ocean thermal, high-altitude wind, concentrated PV solar power, etc.-all have considerable potential, but they need further research, development, and deployment to become mainstream energy sources. In the distant future, space-based solar power or fusion might become dominant energy sources, but as yet they require decades of additional development.

The following illustrates projected future costs of electricity generation from various sources. In blue are estimated direct retail costs, while in green are estimated external costs. The chart represents one important dimension in understanding the future electricity mix. It does not take account local economic conditions, the size of the resource base, and the time and investment required to achieve the projected cost. These issues are discussed throughout the paper.



Importance of Research, Development, and Deployment

There is a long road between a concept and a commercially mainstream technology. Any proposed energy technology must undergo basic research, demonstration, commercialization, and final scaling up to achieve economic competitiveness. At each of these steps, the technology could fail. Furthermore, the private sector is reluctant to take full responsibility for the investment risk of emerging technology, a reluctance that is more pronounced the earlier the technology is in the development process. Thus, the development of new technologies often requires partial or full support from the public sector. This has been the case in the history of nuclear power, solar, and wind, as well as with many technologies not directly related to energy production [85].

Because the costs of doing research are concentrated and the benefits are diffused, a free market without government intervention will tend to invest less in basic research than is socially optimal [72]. The public benefit of research is called R&D spillover.

From 2005 through 2013, the International Energy Agency member countries spent about $140 billion on energy research and development, including about $24 billion on energy efficiency [58]. Over the same period, the United States spent about $51 billion on energy research, or $5.6 billion per year on average. By comparison, the production tax credit in the United States is estimated to "spend" (via foregone tax revenue) $36.4 billion from 2008 to 2018, or $3.3 billion per year, most of which now goes to the wind industry [127]. In 2012, the Congressional Budget Office found [29] that energy research had decreased from $10.5 billion to $3.6 billion from 1980 through

2012, with a spike in 2009 due to the American Recovery and Reinvestment Act. By contrast, energy-related tax credits were at $21.5 billion in 2011. The CBO reports [29] that research at the early stages of technology development is generally more effective than later stage research and often produces a positive return on investment, although in the United States, government R&D spending is modest, compared to other energy support mechanisms. American and global research figures are very small, compared to a world energy market estimated at $6 trillion annually [125].

There are other policy routes toward an energy future not dominated by fossil fuels. Since fossil fuels carry significant negative externalities, such as climate change, it makes sense to tax them accordingly. Some studies [94], [102] have found that a carbon tax, levied on sources of CO_2 emissions throughout the economy, may be economically beneficial, even without taking into account a reduction in climate change. However, these benefits are predicated on the efficient recycling of tax revenue back into the economy [117].

Another set of policy approaches is direct support for fossil fuel alternatives. Such support might take several forms. A renewable energy mandate is a law requiring that a utility procure a certain percentage of its power from designated renewable sources. A feed-in tariff is a long-term contract to purchase energy from renewable sources at fixed prices. In the United States, the Production Tax Credit (PTC) and Investment Tax Credit (ITC) are paid by the government, for per-kilowatt-hour production of and for dollars of investment in designated energy sources, respectively.

The above policies may be useful tools for bringing an early-stage commercial technology to a mature stage, at which it could compete without further support. However, they have limitations and drawbacks. None of the foregoing support policies are effective in developing a pre-commercial technology, and as we will show, the most promising future energy technologies are those not yet commercialized or only in their very earliest stage of commercialization. A mandate or direct financial support has the risk of supporting inefficient technologies or those with serious drawbacks, as is the case with the Renewable Fuel Standard [96]. Finally, subsidies for any energy source might artificially depress the price, thereby discouraging both efficiency and conservation [92].

Most Strategic Investments

To best insure a prosperous energy future, governments must select a research portfolio. Different energy technologies require different levels of investment and different lengths of time to reach full commercial maturity. Furthermore, it is difficult predict in advance which technologies will be successful, so placing too much hope in any one investment is very risky. Moreover, not all potential investments are equally promising, and limited resources require that governments build their research portfolios strategically. Our goal in this paper is to identify the best areas for investment.

Wave Energy

The capture of the kinetic energy of ocean waves has great potential. The resource base in the world's oceans is enormous, even when attention is restricted to near-shore waters. In several countries, including the United States, wave power has the potential to supply a significant fraction of energy needs. Due to the high power density of ocean waves, wave energy also has the potential to be less expensive than wind power.

However, the industry has been slow to develop, due to the engineering challenges of constructing devices that can withstand harsh ocean conditions. Our analysis shows that the considerable energy potential of the ocean might be unlocked with modest investments in research and industry support.

Enhanced Geothermal Systems

Today, geothermal power occupies a useful niche in the world's energy picture. It is cheap and reliable, although its reach is limited by the geography of conventional geothermal power. Enhanced geothermal systems (EGS) could be deployed economically over large portions of the world, especially if used to for low grade industrial heat. The resource base is enormous, and EGS is one of the most environmentally benign energy sources in existence or under development.

Concentrated Photovoltaics

Concentrated photovoltaics comprise a small but rapidly growing subset of the solar market. It is likely to overtake conventional PV solar in cost performance, and concentrated PV has smaller land requirements than conventional form. The resource base for solar power is essentially infinite. As with other intermittent sources, widespread deployment of concentrated PV will require strategies to respond to intermittency.

Industrial Carbon Capture and Sequestration

Carbon capture and sequestration (CCS) is the most promising opportunity for reducing emissions from high temperature industrial processes, such as in the iron and steel or chemical industries. Once developed, industrial CCS should, in most of the world's staple heavy industries, become less expensive than the damage caused by emissions. However, a successful CCS policy must include both technology development and a regulatory framework to insure that the technology is deployed.

Other Good Investments

The following investments, though not as compelling as those listed above, are nevertheless worthy of inclusion in a balanced energy research and development portfolio.

Algae Biodiesel

There are fewer viable low carbon alternatives for liquid fuels than there are for electricity production. Recent research programs have brought algae biodiesel within reach of commercial viability. Furthermore, algae biodiesel has the potential to reduce emissions relative to conventional diesel or gasoline and requires far less land to produce than other biofuels. However, due to the high energy requirements in the production process, significant emissions are likely to remain.

Current Nuclear Power

Nuclear power is difficult to finance in a liberalized electricity market due to high capital costs and long construction times. However, nuclear is the only mainstream low carbon, base-load power source available (other than hydroelectricity, which suffers its own limitations-see below). There are no obvious pathways for significant cost reduction without technology advancement, and thus contemporary nuclear technology will likely always require government support. However, to foreclose the nuclear option would be to abandon the only surefire route to a decarbonized electricity sector, and this is a severe risk to take.

Next Generation Nuclear

Research into small modular reactors and Generation IV nuclear technology promises to reduce costs and overcome the limitations of today's nuclear technology. In addition, high-temperature gas-cooled reactors are among the few options for low carbon, high grade industrial heat. Small modular reactors could be available by the 2020s, followed by Generation IV reactors in the 2030s. However, such research programs, especially for Generation IV concepts, will be expensive and bear uncertain results.

Fusion

Fusion energy holds tremendous potential. However, a successful fusion research program will cost tens of billions of dollars and (if successful) result in commercial fusion power plants no sooner than the 2050s. Due to the great uncertainty of what will both work and be economical, a fusion research program should cover a range of potential technologies, including magnetic confinement and inertial confinement.

Conventional Wind

Wind power is currently the most advanced of the renewable energy sources and in some markets is now competitive even without subsidies. There is little remaining potential for cost reduction in conventional wind power. However, such cost reductions are worth pursuing, since a viable wind market already exists.

High Altitude Wind

There is great uncertainty regarding the feasibility, potential resource, and environmental impact of high altitude wind power. Since the technology is in the very early stages of development, only modest investments may be required to determine whether high altitude wind has a future in the energy mix.

Luminescent Solar Concentrators

Luminescent solar concentrators (LSC) are another concept with uncertain potential. Compared to today's photovoltaic technology, LSC is expected to have much less intermittency, and to be easy to deploy in urban environments. The technology remains in a basic research state, and it is unclear how economically viable it might become.

Hydrothermal and Binary Geothermal

Today's geothermal technologies provide affordable base load power with minimal environmental side effects. Prior to the deployment of enhanced geothermal systems, binary geothermal plants are a promising growth area in the geothermal market. However, to a lesser degree than hydrothermal but a significant one nonetheless, binary geothermal is limited by geography and the resource base.

Ocean Thermal

Ocean thermal exchange converters (OTEC) draw upon a large resource base and could produce clean, base load power. However, they are not likely to be economically viable, except perhaps in limited island markets, unless their electricity production can be supplemented by additional co-products, such as fresh water or open ocean mariculture.

Unpromising Investments

The following investments show little prospect of making significant contributions to the world's energy mix without severe environmental damage, and they should not be pursued as solutions.

Coal

The efficiency and pollution levels of coal-fired power has been gradually improving over time. Nevertheless, there appears to be no viable path to coal power that is both economical and acceptably clean. Government policy should be oriented toward making coal obsolete rather than improving it.

Natural Gas

Natural gas is much cleaner than coal as a source of electricity and is often touted as a bridge fuel that reduces emissions and pollution until better alternatives can be deployed. While government policy should favor a shift from coal to natural gas when those are the only two options, gas-fired power is a mature and low-cost technology that not really need of support. Instead, government policy should aim directly for a post-fossil fuel future.

Petroleum

Although alternatives to petroleum-based fuels in the transportation sector are not systematically evaluated in this report, we believe that they, rather than increased petroleum production, should be the focus of public energy policy.

Carbon Capture and Sequestration on Fossil Fuel Plants

Carbon capture and sequestration will reduce emissions at coal and natural gas plants, but it is likely to render such plants uneconomical. Thus CCS on fossil plants will, at best, remain in deployment for a short period.

Biomass Power

Biomass power, including waste to energy systems, is expensive and can draw upon a limited feedstock until dedicated energy crops need to be produced. The latter scenario results in high land use requirements and a potentially heavy greenhouse gas impact due to land use changes. Furthermore, biomass power is likely to always remain more expensive than other mainstream power sources.

Current Generation Biofuels

Today's biofuel technologies are not economical without government support and probably never will be. Furthermore, biofuel production requires substantial land and water resources, making it an unsuitable option for large scale energy production.

Hydroelectricity

There is significant potential in the world to expand deployment of hydroelectricity, but it will never be more than a small share of the world's energy mix. Furthermore, hydro power can have severe ecological impacts on the river and local region. Each hydro project should be judged on its own merit, and perhaps some should be completed, but hydro is not a major energy solution.

Offshore Wind

Offshore wind power draws upon a large resource basis and provides steadier power than conventional wind. However, the evidence is that it will always remain too expensive to be a mainstream power source.

Conventional Solar PV and Concentrated Solar

Despite the history of cost reduction, conventional solar photovoltaics will probably remain more expensive than other mainstream power sources for decades to come. This, together with the problem of the intermittency of the resource, makes them uneconomical. Compared to solar PV, concentrated solar power has fewer intermittency issues but higher costs; it also shows little evidence of sufficient future cost reductions. In addition, both of these solar classes of solar have large land requirements. With recent price reductions in solar cells, higher efficiency is becoming a more important goal, and thus thin film cells are also not likely to be economical.

Other Marine and Hydrokinetic

Aside from wave and ocean thermal power, both discussed above, other marine and hydrokinetic power sources include tidal, river current, and osmotic power. In each of these cases, the resource base is too small for the energy source to play more than a niche role in the world's power supply. In addition, while they do not generate much pollution in their own life cycles, these power sources must be deployed in ecologically sensitive areas.

1 Basic Concepts

In this section, we discuss the common concepts that are used to evaluate energy technology options.

Our focus is mainly on electricity, with some discussion of options for transportation fuel and industrial heat. Due to the limited number of options being considered for the latter topics, the economic discussion will be more qualitative. We shall present here a more rigorous and quantitative view of the economics of electricity production.

Levelized Cost of Electricity

The bottom line measure of the price of electricity is typically its levelized cost (LCOE). This is the price P, given in US cents per kilowatt-hour, that a power plant must receive for its generated electricity in order to break even. Such a price is calculated with a discount rate d, which represents the rate at which future costs and revenues are devalued. The choice of d is important. Higher discount rates tend to favor projects with shorter lives and higher operations and maintenance (O&M) costs rather than capital costs.

We shall now illustrate the LCOE of a hypothetical power plant. Suppose the plant has a nameplate capacity of 1 GW and a capacity factor of 80%. This means that on average, it produces 80% of full power, or 800 MW, equivalent to 7008 GWh (gigawatt-hours) per year. Suppose that the plant has a capital (also called overnight) cost of $5000/kW, or $5 billion total. Suppose that O&M, including any fuel, cost $100/kW/year, or $100 million per year. Finally, suppose the plant has a life time of 50 years.

At a 5% discount rate, the levelized cost of the plant is $6.92 billion. If electricity has a constant price P over the 50 year life of the plant, the total levelized revenue of the plant is 134 billion $\times P$. The plant breaks even when P = $0.051, so the LCOE is 5.1 ¢/kWh. If instead we use a discount rate of 8%, then the LCOE is 4.7 ¢.

[Unless otherwise noted, all monetary values in this paper are given in US cents per kilowatt-hour, inflation-adjusted to 2015 levels.]

Externalities

In measuring the cost of any energy source, the quoted LCOE (price) often takes into account only the direct costs to the producer. However, our research is motivated by costs, particularly health and environmental ones, not paid by either the producer or the consumer. These are called externalities, and because they are paid by society at large, they do not generally factor into economic decisions about energy. Some externalities have their beneficial aspects, but most of the ones discussed in this paper are harmful.

Although it may seem crass to express damage to the climate, human health, and wildlife in monetary terms, the fact remains that somehow decisions about energy production need to be made, requiring a single evaluation of all costs and benefits. Whether or not it is acknowledged, economic and policy decisions regarding energy reflect an implicit price on its externalities. It is therefore best to make them explicit. Furthermore, monetizing health and environmental damages offers a succinct method to compare costs of different options, while a strictly qualitative assessment can obscure decision-making.

For example, opponents of nuclear power often cite the release of radioactivity, problems of waste disposal, and risk of a severe accident as reasons to reject nuclear technology. However, our data suggests that these costs, expressed in a per kilowatt-hour basis, are comparable to the external costs of renewable energy sources, and are much less than those of fossil fuels. Without quantifying costs, it is very difficult to make reasoned judgments about the relative merits of different options.

Nevertheless, we have not been able to monetize all external costs of energy production. For example, two major costs not monetized are land use requirements and damage to wildlife. In this paper, we have made the qualitative judgment that the land use requirements of biofuels and solar power should be regarded as major costs, while the direct wildlife deaths resulting from energy sources such as wind and wave power are to be considered minor. Numerical estimates of these costs, perhaps based on an ecosystem services analysis, would provide much additional valuable insight. The external costs of an energy source can depend greatly on the specifics of a particular project, such as the ecological and population characteristics of a given site or the design of the project. Where we can, we shall use average estimates when evaluating the merits of general technology investments. Decisions about individual energy projects must take into account site-specific characteristics.

We have given particular attention to the externality of climate change. All energy sources being considered here result in some emissions of greenhouse gases. Some emissions are direct, while others are the indirect result of the manufacturing, maintenance, and/or decommissioning processes. We use a social cost of carbon of $45 per ton [56] to measure this externality, though there is considerable debate as to the appropriate value. Futhermore, damages in the future are estimated to be higher than they are today [56].

An additional negative externality of electricity production is the cost of maintaining the electric grid. This is particularly potent when discussing such intermittent energy sources as wind and solar, where large, sudden, and unexpected variations in the power produced by the plants creates a challenge in keeping electricity production and consumption in balance. These costs are also highly site-specific, though we have given numerical estimates where we can. (We do not in this survey give a detailed evaluation of methods for managing intermittency.)

Estimating Future Costs

It is difficult to predict with high precision the future cost of an energy source, especially one that is not yet commercialized. The estimates cited in this paper generally use one of two methods for doing so.

The first method is a bottom-up analysis. If the general design of an energy technology is known, then one can estimate the cost of each component and the costs of manufacturing, installing, and maintaining a power plant.

The second method is the learning curve analysis. This is based on the observation that as a technology is deployed, its price tends to decline in a somewhat regular way as a result of economies of scale, standardized manufacturing, and developed supply chains [91]. The learning rate r is the percentage reduction in price that results from a doubling of installed capacity. For example, suppose a given energy technology at the cusp of commercialization has a capital cost of $10,000/kW, a learning rate of 10%, and 100 MW have been installed. Once 200 MW are installed, the cost should be $9000/kW. The cost should be $8100/kW at 400 MW of deployment, $7290/kW at 800 MW of deployment, and so on. Sometimes this phenomenon is expressed as a progress ratio, which is 100% minus the learning rate. In the above example, the progress ratio is 90%.

2 Fossil Fuels

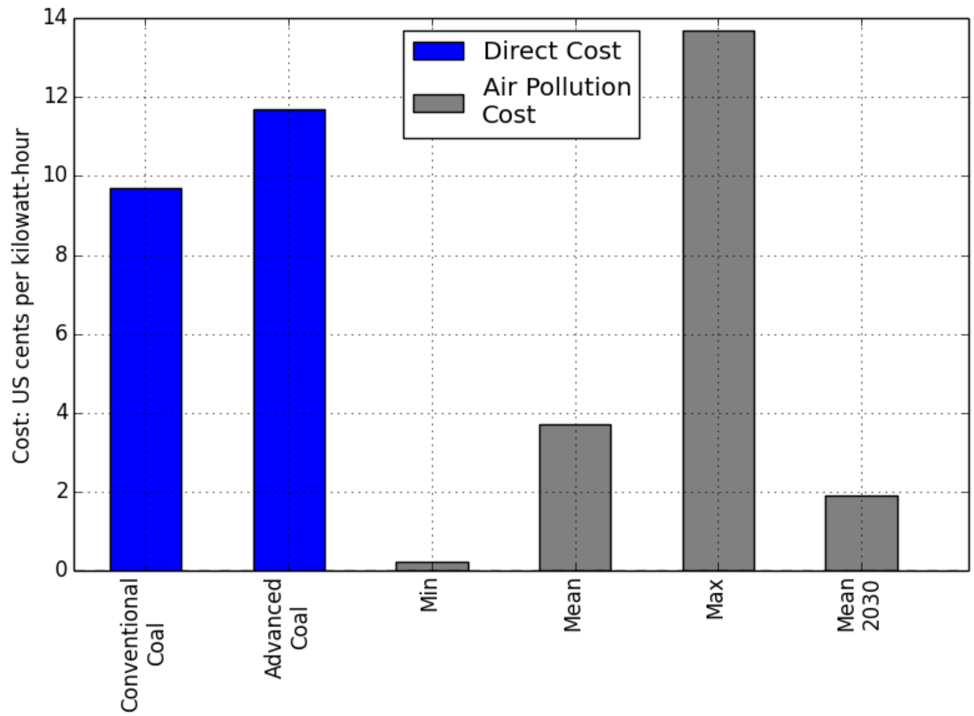
Fossil fuels (coal, oil, and natural gas) form the basis of the world's energy supply and are fundamental to the modern economy. Fossil fuels together comprise 87% of the world's primary energy usage: 33% from oil, 30% from coal, and 24% from natural gas [14].

The combustion of fossil fuels for energy has severe negative external impact on the world's economy. Fossil fuels release air pollution that harms human health and the environment. The CO_2 emissions released from burning fossil fuels play a major role in global warming, which brings severe economic impact. Since these damages are not reflected in the price that customers pay for fossil fuel energy, they represent a severe inefficiency in the energy economy. These are essential motivations behind public efforts to develop alternative energy sources. All energy sources have at least some externalities that are not priced in the market, but for fossil fuels the externalities are particularly severe.

Coal

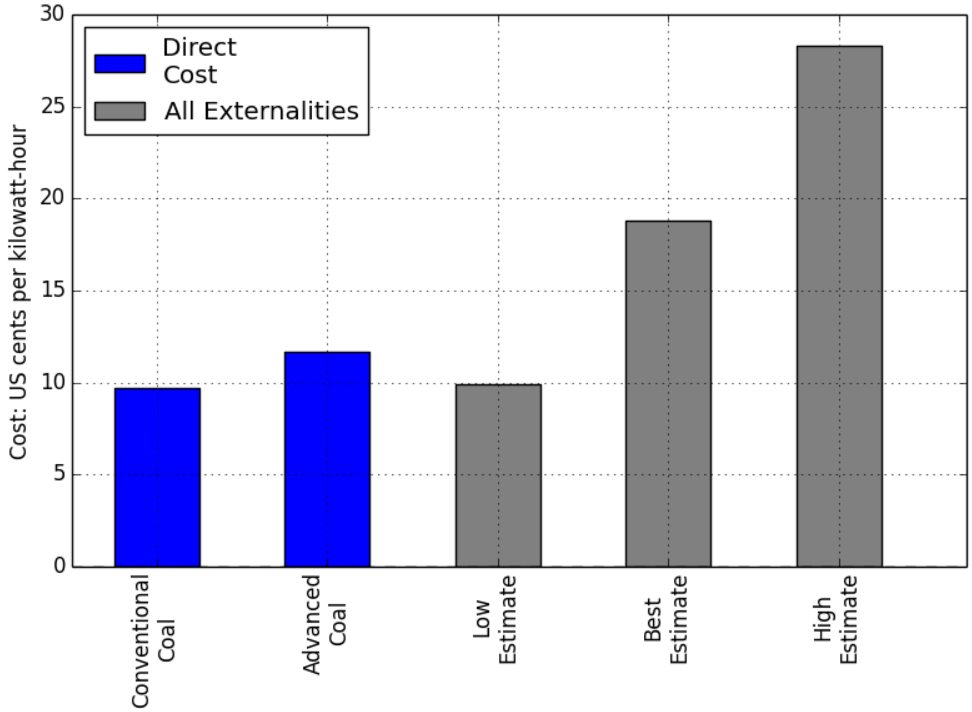
Coal remains dominant in the electricity sector, providing 40% of the world's electricity production in 2013 [144]. At 2013 rates of production, estimated reserves of 869 billion tons are expected to last for 115 years. Reporting of reserves is limited and true coal reserves might be four times as great. Furthermore, the growth rate in absolute terms of coal exceeds all other energy sources, with almost all of the growth occurring in developing countries [144]. In the United States, the Energy Information Agency estimates the price of coal-fired electricity coming online in 2020 at 9.7 ¢/kWh [36], while the figure is 11.7 ¢ for advanced coal. Absent a change in energy economics, the burning of coal for electricity, with all of the negative consequences detailed below, will remain dominant for the foreseeable future.

For coal-powered electricity, aside from global warming, the largest externality is air pollution from the combustion of coal. The main pollutants are sulfur dioxide (SO_2), nitrous oxide (NO_x), and particulate matter, each of which causes serious health damage to humans. These pollutants have additional external economic impact, such as reduced crop and timber yields and damage to scenic vistas. In 2005, the National Academy of Sciences [19] examined 406 plants, representing 95% of the total at the time, and found that they caused a collective $71 billion of pollution damages, or about 3.7 ¢/kWh. Due mainly to variation in pollution control, damages from individual plants range from 0.22 ¢(5th percentile) to 13.7 ¢(95th percentile). The average pollution damage is estimated to decrease to 1.9 ¢ in 2030 due to enhanced pollution controls. (This report predates the Environmental Protection Agency's Clean Power Plan proposal.)



Coal mining and distribution present additional costs. Mining of coal in the United States is typically done through underground or surface mining, or with mountaintop removal. These practices, particularly mountaintop removal, cause significant additional ecological impact. In addition to air pollution, the combustion of coal releases heavy metals into the atmosphere, which cause human health damage. Of particular concern is mercury, which bioaccumulates in the food chain. The combustion of coal leads to coal ash as a byproduct, which needs to be managed and presents a hazard to human health and the environment. Most coal in the United States is transported by rail, and 241 deaths in 2007 resulted from rail accidents attributable to coal trains. Valuing the deaths at $6 million per person, the cost is about $1.5 billion [19].

Epstein's 2011 study [40], taking a broader view of the externalities of coal, found a best estimate of 18.8 ¢/kWh of external costs, with a range of 9.8 to 28.3 ¢. The best estimate figure includes 5.2 ¢ of damages associated with mining and transportation and 3.2 ¢ of damage associated with climate change. With a potential improvement from 33% to 50% efficiency, we estimate the external costs of advanced coal at 12.4 ¢/kWh.



The full lifecycle greenhouse gas emissions of coal generated from electricity is estimated to be the equivalent of 820 g-CO_2e/kWh (grams of CO_2-equivalent per kilowatt-hour) [123]. A social cost of carbon of $45/ton yields climate change damages of 3.69 ¢/kWh of damage.

One area for improvement in the impact of coal-fired electricity is the increase in plant efficiency. This has been gradually rising over time and was about 33% on average in 2007 [11]. However, there is a trade-off in plant design between efficiency and cost: higher efficiency requires that the plant operate at a higher temperature and pressure, which in turn requires stronger materials, more careful engineering, and more maintenance. Supercritical plants operate at a pressure of 250 bar and temperature of 500 °C and have efficiencies of 41.5%. Ultra-supercritical (USC) plants operate at a pressure of 300 bar and temperature of 600 °C, with efficiency 45% [10]. Further improvements in USC technology, driven by advances in material science, should achieve an efficiency of 50% [10]. This would result in as much as a 25% reduction in CO_2 emissions compared to subcritical plants. The EIA cites a direct cost of 11.5 ¢/kWh for advanced coal [36].

Over time, the impact of pollution has been lessened by pollution controls. Since the Clean Air Act of 1970, coal plants have installed flue gas desulphurization (scrubbers) and selective catalytic reduction (SCR). These technologies have produced a cost to efficiency of 2% and 1% respectively [11]. The expansion of these technologies over time will nevertheless reduce the health and air pollution impact of coal on a per-kWh basis. However, scrubbers and SCR will not address global warming since these technologies do not capture CO_2.

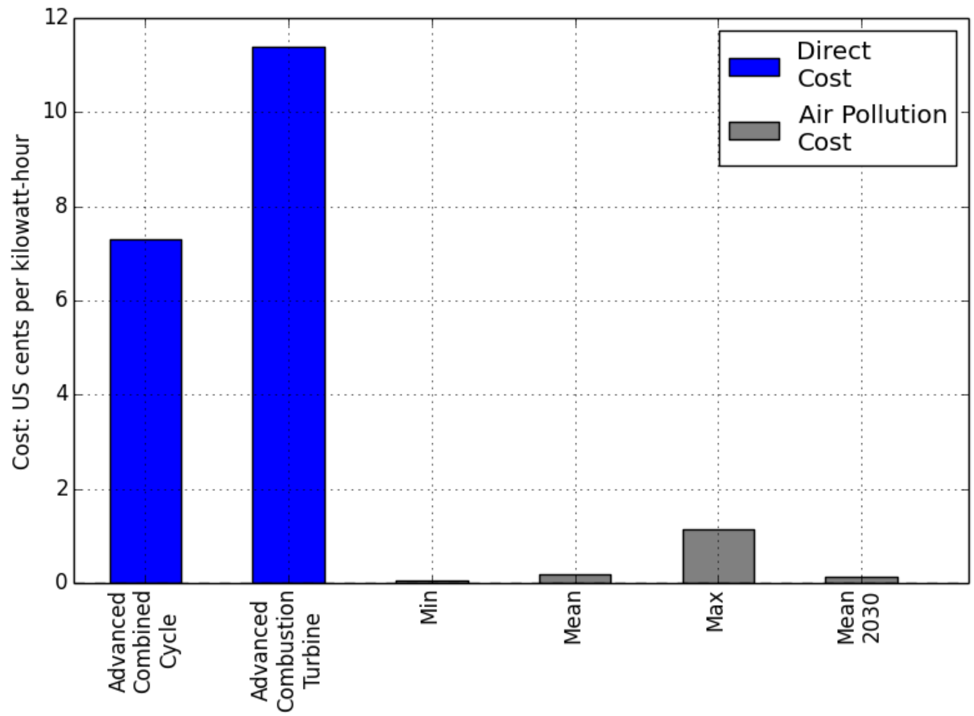
Absent carbon capture and storage technology, the rising social cost of carbon [56] will at least match improvements in coal plant efficiency, keeping the climate change damage of coal power above 3 ¢/kWh. Improvements in efficiency could reduce the damages of coal mining and transportation to 4 ¢, and with improved technology, the projected air pollution damages in 2030 are 1.9 ¢. Despite all the potential for improvement, the health and environmental cost of coal combustion will remain high.

Natural Gas

After coal, natural gas is the largest source of energy for electricity and is also growing rapidly. This is particularly so in North America, where natural gas supply has expanded due to rapid progress in shale gas. This is likely to continue well into the future. In 2011, natural gas production was 3518 billion cubic meters (bcm) and reserves were 209,742 bcm. This gives a reserve-to-production (R/P) ratio of 60 years [144]. World shale gas reserves might be much larger; in 2013, the World Energy Council estimated them at 456,000 bcm, giving an R/P ratio of well over 100 years at projected 2030 consumption [144]. The true value is likely to be much higher, as much of the world has not yet undergone full shale gas exploration. Demand is projected to increase to 4700 bcm in 2030, including the following: 900 bcm for commercial and residential use, 1200 bcm for industry, 1900 bcm for electric power,and 150 bcm for transportation [144]. Thus the replacement of natural gas with lower carbon energy sources is a multi-faceted challenge.

Advanced in drilling technology have made natural gas one of the least expensive electricity sources. In the United States, a conventional combined cycle natural gas plant to come online in 2020 will produce electricity at 7.4 ¢/kWh. An advanced combined cycle plant has an LCOE of 7.1 ¢. Advanced combustion turbines, which are an important tool for load balancing, have an LCOE of 11.0 ¢[36].

The air pollution damages of natural gas electricity, excluding global warming, are more benign than coal. A sample of 498 gas plants, representing 71% of US natural gas electricity, was found to cause $844 million of damages from air pollution. This translates to 0.18 ¢/kWh. As with coal, gas plants have high variance in their pollution damages, ranging from 0.06 ¢(5th percentile) to 1.14 ¢(95th percentile). The average pollution damages are predicted to decrease to 0.13 ¢ by 2030 [19].



The air pollution damages (again, excluding global warming) of natural gas used for direct heat are estimated as follows: 13 ¢/tcf (thousand cubic feet) for commercial, 11 ¢ for residential, and 9 ¢/tcf [19] for industrial. One kWh of electricity is generated from roughly 0.01 tcf of natural gas [34], and thus direct use of gas for residential or industrial heat is slightly less polluting than electricity conversion, by volume of gas.

Natural gas production creates additional externalities, such as water consumption and pollution, through the drilling and extraction process. Modern methods include hydraulic fracturing, in which high pressure fluids are injected into a well, to fracture the rock and increase the flow of gas. These costs do not seem to be very great; in 2015, the US Environmental Protection Agency found that widespread water pollution has not resulted from hydraulic fracturing, although more research is needed [38].

The full lifecycle greenhouse gas emissions of electricity generated from natural gas are estimated to be the equivalent of 490 g-CO_2e/kWh [123]. This figure includes methane leakage in the extraction and transport of gas. A social cost of carbon of \$45/ton prices the climate change damage of natural gas electricity at 2.2 ¢/kWh. According to an analysis commissioned by the U. S. National Energy Technology Laboratory [129], the major conventional and unconventional sources of U.S. natural gas have upstream emissions ranging from 22 to 33 g-CO_2e/kWh. Liquified natural gas has higher upstream emissions, 66 g-CO_2e. Meanwhile, upstream emissions of carbon monoxide (CO) and NO_x do not differ greatly by source of gas, except that offshore gas has lower emissions in both categories. There is ongoing debate as to whether hydraulic fracturing results in significantly more methane leakage, and hence worse climate impact, compared to conventional gas production [73].

Natural gas does reduce air pollution and greenhouse gas emissions considerably relative to coal. However, emissions remain too high to consider gas a permanent solution for climate change.

Petroleum

Oil remains the single largest component of the world's energy supply and is hence critical to the world's economy. Oil consumption grew from 66 million barrels per day in 1991 to 88 Mbd in 2011. Yet the reserves to production ratio over the same period increased from 43 years to 54 years [144]. Much of the increase in recent years has been driven by unconventional oil forms: heavy oil, tar sands, and tight oil (that is, oil that is difficult to extract due to low permeability). In addition, higher prices since 2003 have supported the development of unconventional oil types [144]. It thus seems unlikely that a peak in world oil production will occur soon, although growing reliance on these unconventional oil forms might raise prices in the long term. Nevertheless, the oil price has historically been volatile, with a dramatic drop in late 2014, and is thus difficult to predict.

Petroleum-based fuels remain the primary energy source for transportation. Non-climate air pollution damages associated with gasoline combustion in light-duty vehicles are estimated at about 1.6 ¢/VMT (cents per vehicle-mile traveled) in 2005, which is about 33 cents per gallon of gasoline [19], assuming the gasoline is refined from conventional oil. The life cycle of gasoline includes the extraction and transportation of crude oil, refining of crude oil, and the transportation and distribution of refined products. Each of these phases contributes to the external costs of gasoline.

Oil shale is often considered a long term solution, due to the limitations in crude oil supply. Oil shale contains the organic compound kerogen, from which shale oil can be extracted. Oil shale reserves are estimated at 4.8 trillion barrels (150 years at 2011 oil production rates), although it is uncertain what portion of these reserves will be economically recoverable [144]. Oil shale is more difficult to extract that conventional oil, and it will require a high price–around $70-100 per barrel–to be economically competitive [144]. In addition, oil shale produces 25% to 75% more CO_2 emissions during its production cycle than conventional crude [144]. Conventional crude has a CO_2 content of 317 kg per barrel [13], so if CO_2 is priced at $45/ton, then carbon pricing would add $3.60 to $10.70 per barrel to the price of oil shale relative to conventional crude. The prospect of even more expensive and carbon-intensive transportation fuel in the future increases the urgency of developing alternatives.

Carbon Capture and Sequestration

A carbon capture and sequestration/storage (CCS) system is designed to remove CO_2 at the source of emission, such as a coal or natural gas plant, and store it in an underground chamber. There are four major ways in which CCS can be employed: separation of CO_2 from flue gas resulting from fossil fuel combustion, removal of CO_2 in the production of synfuels from fossil fuels or biomass; oxy-fuel combustion, and inherent separation of CO_2 in industrial production processes [60]. The technology is still under development and not yet ready for widespread commercial deployment.

The IEA has developed a CCS technology roadmap [60] that holds global warming to 2 °C. About $3.7 trillion would have to be invested in CCS until 2050 to sequester 120 Gt of CO_2. Such an investment represents a $31/ton valuation of CO_2 removal, well below the estimated social cost of emissions. Of the CO_2 captured, 45% would come from heavy industry, such as iron and steel, cement, and biofuels. In these industries, electricity generated from renewable sources is not a suitable replacement for fossil fuels in high-temperature processes [60]. Key areas of R&D and public support for development of CCS include exploration of storage sites, cost reduction of capture technologies, and development of alternative uses for the captured CO_2, such as hydrogen production [60].

In 2011, seven staple industries of the modern economy–aluminum, pulp and paper, natural gas processing, refining, chemicals, cement, and iron and steel–produced 7 billion tons of CO_2 out of 31 billion total emissions [107]. Under business as usual, that number is projected to grow to nearly 10 billion tons by 2050. Heavy industrial emissions result from high temperature processes, for which electricity is not cost effective, and from other sources inherent to production. Absent CCS, an estimated 30% of CO_2 emissions could be reduced from heavy industry through efficiency and other economically viable techniques; and CCS is the only technology on the horizon that will allow further reductions [107].

An analysis of several industries has shown that, in some cases, CCS is economically viable at modest CO_2 prices [60]. About two thirds of emissions from refining could be captured at $80/ton and most emissions at $105. Most emissions from iron and steel could be captured at $85, while half could be captured at $55. In the chemical industry, most emissions could be captured at $100 and a third at $35. Most emissions in pulp and paper and in cement could be captured at $60. Gas processing, ethanol, and aluminum smelting are particularly amenable to CCS: most emissions in these industries could be captured at $20. Another estimate [48] is that for hydrogen and ammonia production, the CO_2 abatement cost by using CCS would range from $6-80 (2007 dollars), while for other heavy industry, it would be $34-165. Thus, while not all heavy industrial emissions can be captured by CCS at low cost, a substantial fraction can at under $45/ton.

CCS is often considered a solution for mitigating the climate change impact of coal power. Since CCS equipment requires energy to operate, this energy is not available for customers, and the equipment reduces plant efficiency. Estimates of the parasitic load of carbon capture (not including storage) include 5-30% and 10-15% [11]. A 2010 Congressional Research Service survey of CCS technologies [48] estimated that CCS on a new integrated gasification combined cycle plant, using bituminous coal, would add 3-6 ¢/kWh to the price of electricity. On a supercritical coal plant, the price increase is 5-8 ¢/kWh. About 90% of the CO_2 from combustion is removed by CCS, which translates to an 85-88% reduction in emissions, due to its cost to plant efficiency. Furthermore, the reduced efficiency increases the non-CO_2 pollutants from coal power. Installing CCS equipment on existing plants is expected to be more expensive. Comparing a new integrated gasification combined cycle (IGCC) coal plant with CCS to a supercritical plant without CCS, the IGCC plant with CCS is more economically sound, at a carbon price of $45-70/ton-$CO_2$e or above [48]. In either case, the coal plant would be more expensive than other energy sources.

For coal with CCS, we estimate an 86.5% reduction in CO_2 emissions to Epstein's study. This gives an external cost of 15.6 ¢/kWh. The EIA estimates that the direct cost is 14.3 ¢/kWh [36].

On natural gas combined cycle plants, CCS is estimated to raise the cost to between 8 and 10 ¢/kWh and reduce efficiency from 57% to 48% [60]. We use the EIA's figure of 9.9 ¢/kWh [36]. Due to the reduction in efficiency, we take non-CO_2 externalities of natural gas with CCS to be 0.21 ¢/kWh. While affordable, mandating CCS on natural gas plants would reduce the competitiveness of gas relative to nuclear and renewables.

As with any pre-commercial technology, the cost of CCS is highly uncertain. A 2010 study [48] predicts that once 100 GW of CCS technology is applied to power plants, the cost should decrease by 30% from the initial price. A comparable price reduction for SO_2 capture took about 20 years.

A critical challenge in the deployment of CCS technology is the creation of a market. Even if CCS is technologically mature and cost-effective, it will not be deployed unless some public policy, either a mandate or a carbon pricing mechanism, is in place.

3 Biomass and Biofuels

Biomass power is derived from the combustion of living or recently living organic material, while biofuels are derived from biomass. In this section, we examine the economic and environmental implications of biomass power and biofuels.

Economics of Biomass Power

The price of biomass electricity is highly variable, depending on the local price of feedstock, but it generally is high. The International Renewable Energy Agency estimates [66] cost ranges for several biomass technologies. Co-firing, or the burning of biomass along with coal in a traditional coal plant, has the potential to be the least expensive at 4-14 ¢/kWh. All other technologies have a minimum cost of at least 6 ¢. Median costs are estimated at 11.5 ¢ for digesters, 11.5 ¢ for landfill gas, 20.4 ¢ for combined heat and power, 15 ¢ for boilers, and 16.9 ¢ for gasifiers. Thus economical biomass power requires either high electricity prices or low-cost feedstock.

There are two expected sources of cost reductions in biomass power: improved logistics in the feedstock market and technological improvements in the power plants. An analysis of the European wood pellet market suggests 2-25% cost reductions are possible by 2020 [41]. The following capital cost declines are predicted by 2020: wood gasification by 22%, direct combustion technologies by 12-16%, and anaerobic digestion by 17-19% [66]. Even with these cost reductions, biomass power in a competitive and unsubsidized electricity market is likely to play only a niche role. Based on IRENA's figures [66], anaerobic digestion is likely to be the most competitive biomass technology in the near future. Biomass power also suffers from a diseconomy of scale, in which a significant expansion creates economic competition for feedstock and increases feedstock prices.

Waste-to-energy, or the burning of municipal solid waste (MSW) to produce electricity, is a particularly inefficient technology. Its capital cost is $5300-6300 per kilowatt, the most expensive of biomass technologies surveyed [103]. The World Energy Council estimates the LCOE at 12.5 ¢/kWh in the US and Europe [145]. MSW has a heat value of 13.1-19.9 megajoules per kilogram, or 1.8-2.8 kWh/kg at 50% thermal efficiency. The pollution externalities of waste to energy are estimated at $75/ton of MSW burnt, or about 3.3 ¢/kWh [42]. In addition, waste incineration forecloses the possibility of recycling, which is a substantial opportunity cost. Conservatively valuing the economic value of recycling MSW at 10¢ per kilogram, the feedstock of a waste-to-energy plant has an opportunity cost of 3.6-5.6 ¢/kWh. A 2001 study commissioned by the U. S. EPA [39] found that the all recycling industries had gross revenue of $1.66 per kilogram of recycled material.

Environmental Impact of Biomass Power

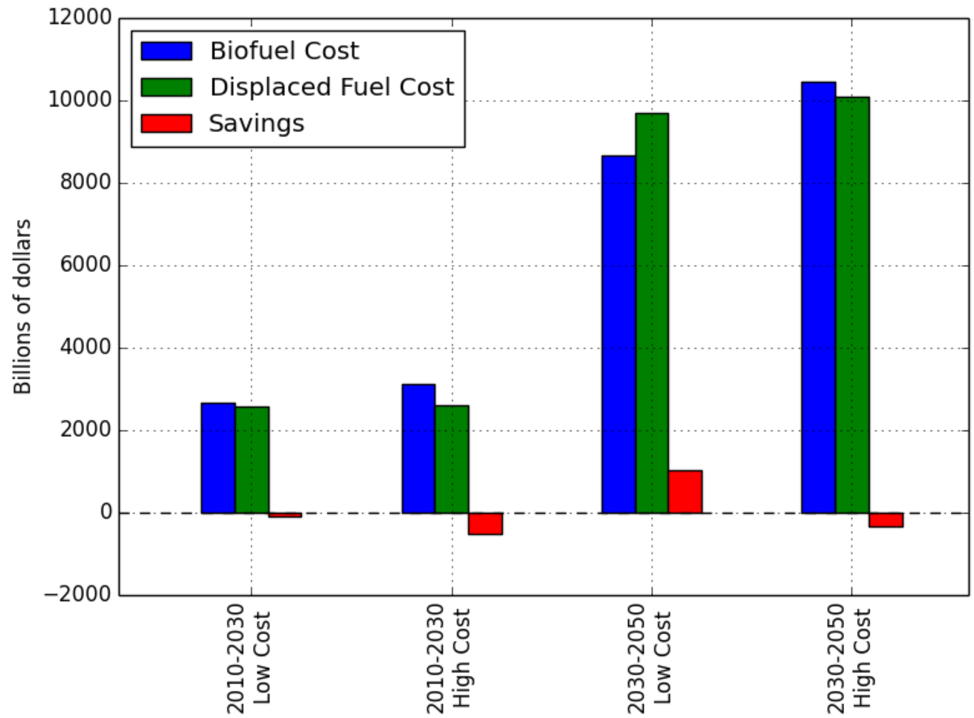
Like internal costs, the external costs of biomass power are highly dependent on technology and location. Furthermore, there is considerable debate as to the impact of biomass usage on the carbon cycle. A 2003 study found that among European countries, biomass externalities ranged from 0 to 4 ¢/kWh, excluding co-firing in Spain [30]. Recent research [143] has found a very low external cost–0.012 ¢/kWh–for biomass power in Northeast China.

For biomass crops produced from dedicated energy crops, the lifecycle greenhouse gas emissions are estimated at the equivalent of 130-420 g-CO_2e/kWh [123]. With a cost of $45/ton of CO_2 emissions [56], the climate change effect should be assigned a cost of 0.6 to 1.9 ¢/kWh. Here too there is great uncertainty and potential variation. A UK study [133] of the greenhouse gas impact of power from woody biomass imported from North America found a wide range of potential greenhouse gas impacts, depending on the effect of the biomass imports on forest management and the time frame examined. The harvesting of boreal residues, which would have otherwise been left to decay can have very small or even negative global warming impact. If the residue would otherwise have been left to decay, the impact can be 425 g-CO_2e/kWh. The harvesting of dedicated energy crops has a wide range of possible greenhouse gas impacts, ranging from negative to higher than coal, depending on the land use counterfactual. In addition, anywhere from 13% to 81% of the energy produced by the biomass plant is required to operate it [133].

It is estimated [144] that the world can sustainably produce 200-500 exajoules (EJ) per year of biomass, compared to an estimated world energy demand of 600-1000 EJ in 2050.

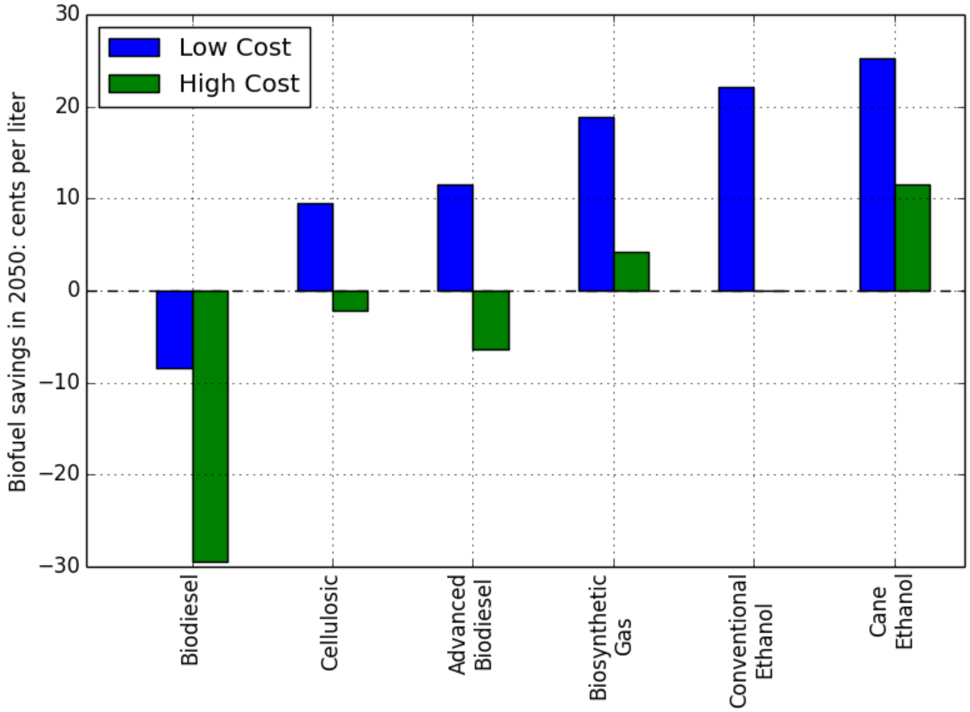
Biofuel Economics

Today's biofuels require large public subsidies and mandates to be economically viable, and this is likely to continue for the foreseeable future. In its Biofuels for Transport roadmap [108], the IEA estimates the biofuel cost, displaced fuel cost, and net savings that will result from the world achieving 27% of transportation fuel from biofuels by 2050. The roadmap models a low and high biofuel cost scenario.



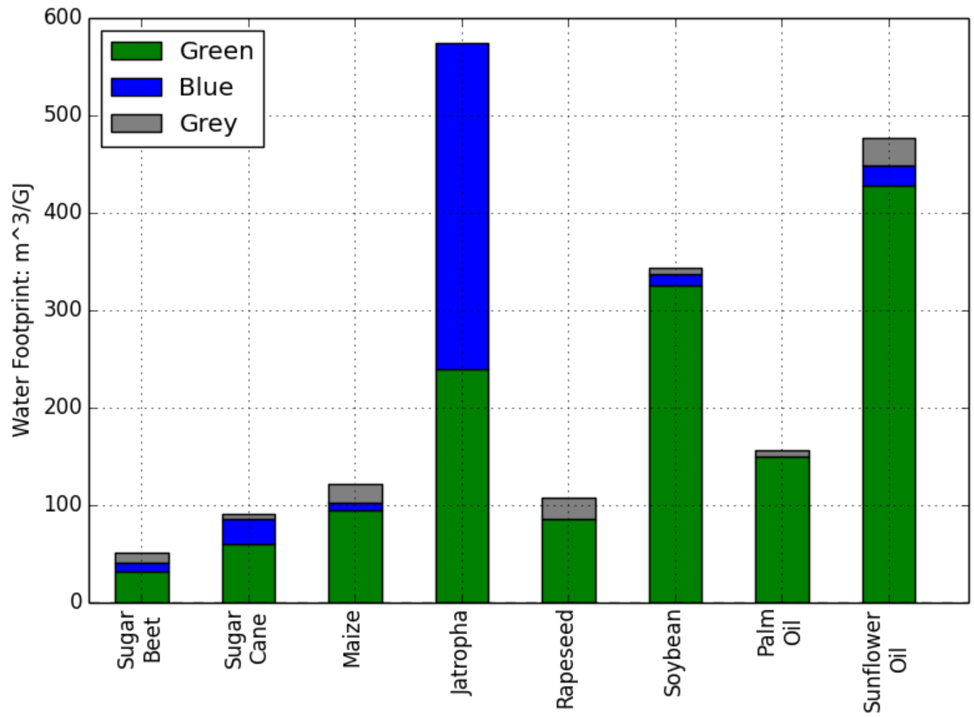
Cost savings cannot be expected until 2030-2050, and then only under optimistic assumptions on biofuel feedstock prices. In the optimistic scenario, the cost savings from 2030-2050 for liquid fuel is about 12%. Furthermore, the IEA scenario assumes a steadily rising oil price, reaching $120/barrel in 2050. This may be unrealistically high in a world in which fossil fuels are undergoing wholesale replacement by alternatives. Low oil prices, such as those seen in 2010, would render all current-generation biofuels uneconomical, even in the IEA's optimistic scenario.

The following shows the cost savings per liter of fuel for various classes of biofuels in 2050, using both the IEA's high- and low-cost scenarios. Only cane ethanol shows a decisive cost savings across the scenarios. Both scenarios again assume oil at $120/barrel.



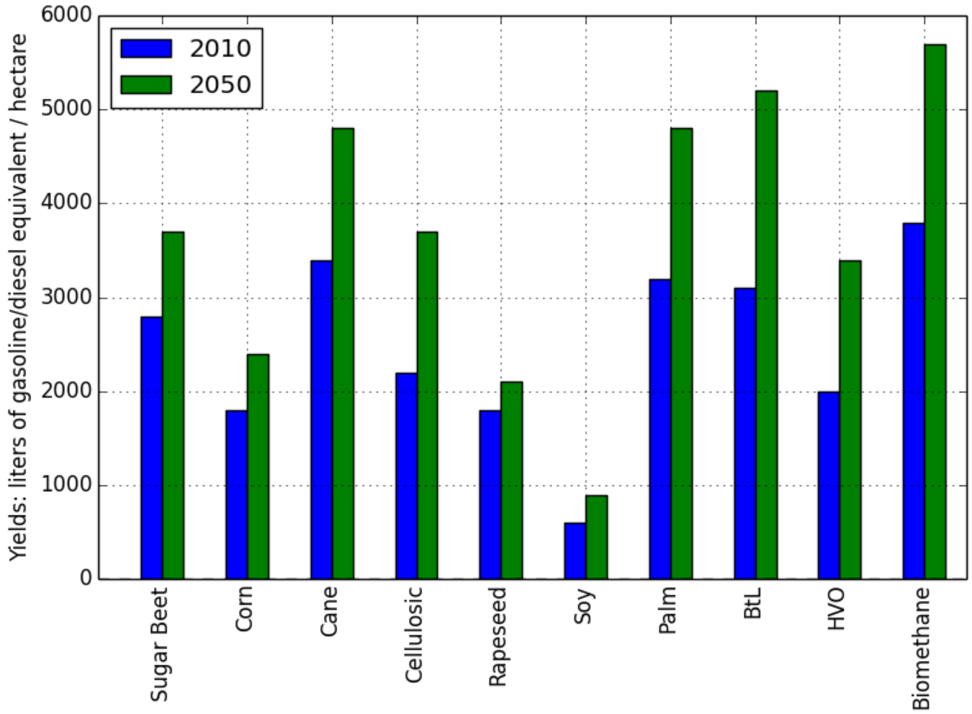
Biofuel Environmental Impacts

Derived from crops, biofuels require considerable land and water resources to produce. The following illustrates the water required to produce biofuels from various crops [84]. Green water is rainwater that would not otherwise be absorbed in the water table. Blue water is water taken from irrigation or streams. Grey water refers to pollution and is the amount of water required to absorb the biofuels' production waste to a safe level. It is debated in the literature whether green water should be included in the lifecycle analysis of biofuels. We include it to assess the feasibility of scaling biofuel production to large levels, since the availability of all forms of water, including green, needs to be considered. See Banja and Dallemand [8], particularly Section 4, for more discussion. Note also that the following are global averages, and depending on climate and agricultural practices, water consumption varies considerably by region.



To give a sense of the scale, the IEA states that 32 exajoules are needed from biofuels in 2050. If this all came from sugar cane ethanol, at 91 m^3 water/GJ, 2912 km^3 of water is needed. This contrasts to 2304 km^3 of world water consumption in 2000 [141]. For biofuels to provide a significant fraction of transportation energy, both a greatly expanded water supply and improved water efficiency are needed.

In addition to water, biofuels are a land-intensive energy source. The following chart illustrates projected biofuel yields per hectare for various biofuel crops in 2010 and projected yields in 2050, given improved agricultural productivity [108].



To illustrate these figures in macroscopic terms, the IEA [108] projects 100 million hectares (Mha) are needed to meet the target of 27% of 2050's transportation fuel coming from biofuel. This compares to 1386 Mha of arable agricultural land as of 2008 [45].

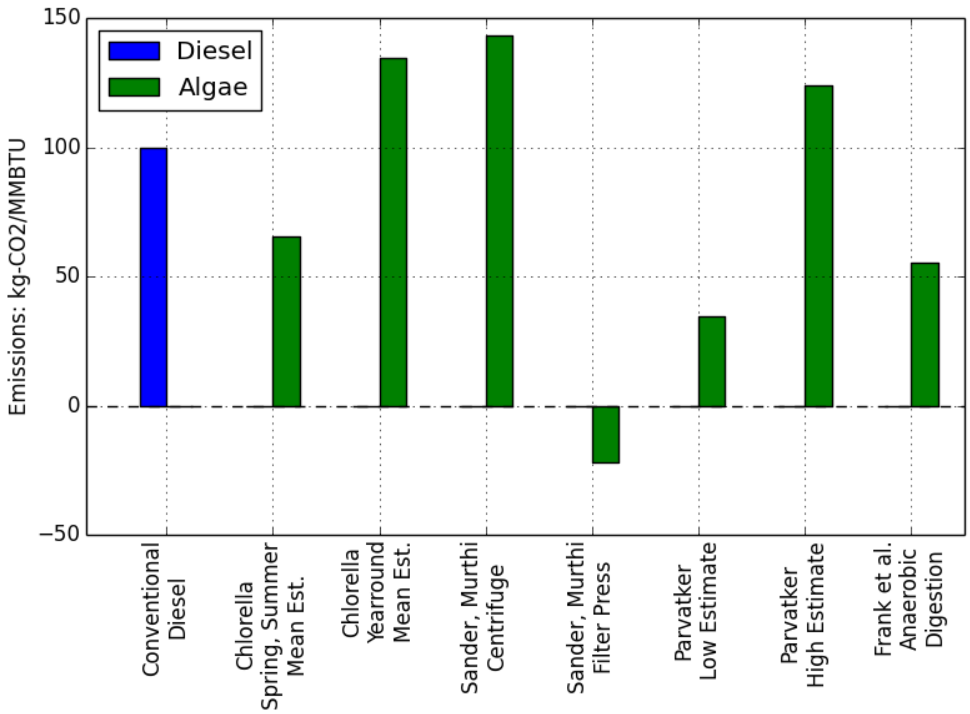
Algae

Algae is a particularly promising potential biofuel feedstock due to improved efficiencies over other feedstocks. Depending on the oil content of the algae, the yields can be 58,700 to 136,900 liters per hectare per year, at least 10 times greater than any alternative [5]. One advantage to algae is the higher oil content: 30% to 70%, compared to 20% for plant crops. Also, algae has a growing time of 5-7 days, compared to months or years for plants.

Algal biodiesel production must still undergo significant R&D before it is cost competitive with petroleum-based fuel. In 2010, as a reinvestment in the algal biofuel research program, the U. S. Department of Energy created the National Alliance for Advanced Biofuels and BioProducts. The program led to four key breakthroughs that reduced the price of algal biodiesel from $240/gallon to $7.50/gallon (nominal currency). They are a genetically modified chlorella algae strain, the Aquaculture Raceway Integrated Design cultivation system, low-energy electrocoagulation harvesting, and a high yield hydrothermal liquefaction extraction technology [79], [97].

There are four key areas in which additional progress is needed to bring algal biodiesel down to $3/gallon to begin to compete with petroleum-based diesel [80]. First is a reduction in CO_2 prices for biodiesel producers, which might be achievd by colocation with CO_2 emitters, such as cement manufacturers. Second is lower liner costs for ponds. Third is a more effective strategy to deal with ash, which can block sunlight and inhibit algae growth. Fourth is recycling of water and the nutrients therein.

Algal biodiesel has lifecycle greenhouse gas emissions comparable with petroleum diesel. Biodiesel from Chlorella algae produces 62.8 to 68.2 kilograms of CO_2-equivalent per million British Thermal Units (kg-CO_2e/MMBTU) of fuel, when it is produced during spring and summer months [97]. If produced year-round, the range is 100.3 to 169.3 kg-CO_2e. These figures contrast to 99.9 kg-CO_2e for petroleum diesel. An analysis by Sander and Murthi [122] found that the lifecycle CO_2 emissions of algae biodiesel depend heavily on the drying process, which can be energy intensive. Under centrifuge drying, lifecycle emissions are 143.3 kg-CO_2e, while for filter press drying, they are much lower if not negligible (-22.1 kg-CO_2e). However, it is questionable whether filter press drying is feasible for large-scale algae biodiesel production [122]. A 2013 study [112] examined the 100-year global warming potential over four algae biodiesel scenarios, with results ranging from 34.6 kg-CO_2e (raceway pond, mechanical extraction) to 124.1 kg-CO_2e (photobioreactor, chemical extraction). Frank et al. [46] estimate that with anaerobic digestion, algae biodiesel has a lifecycle greenhouse gas impact of 55.4 kg-CO_2e.



The conclusion from the available studies is that, compared to other biofuel options, algae biodiesel conserves land but has major climate impact. The major impact comes in the form of fossil fuel inputs into both the growing and conversion processes. However, with the right technology choices, algal biodiesel may bring greenhouse gas savings over petroleum. Raceway ponds perform better environmentally than photobioreactors.

4 Hydroelectricity

Hydroelectric power harnesses the kinetic energy of falling water in a river for electricity production. In this section we focus on dammed rivers. Related concepts include tidal power and river current power, which we discuss later.

Economics and Future Potential

The cost of a new hydroelectric system is very site specific. The International Renewable Energy Association estimates that the levelized cost of electricity from large hydro systems can range from 2 to 21 ¢/kWh; small hydro systems range from 2 to 30 ¢, and refurbishments or upgrades cost 1 to 5 ¢[67]. Like many forms of renewable energy, hydroelectric power is capital intensive. O&M comprise only about 2% to 2.5% of the total levelized cost. The high variability in cost is due to the highly site-specific nature of hydropower. Generally, projects in remote areas or that otherwise have logistical challenges will be more expensive. Smaller projects tend to be more expensive on a per-kilowatt basis. Estimation of the cost of hydroelectricity is further complicated by the fact that dams often have additional economic functions, such as irrigation and flood control. This makes it difficult to assess what portion of the dam's cost should be allocated to electricity production.

Hydroelectricity is one of the oldest forms of electricity available today, with large scale production beginning in the 1880s. It is also the largest non-fossil energy source in the world today [14]. Consequently, it is a already highly developed technology, and there are no clear pathways for significant cost reduction other than general improvements in civil engineering [67].

In 2011, the world produced 2751 TWh of hydropower from 935 GW of installed capacity [144]. Of these totals, the United States produced 268 TWh of hydropower from 77.5 GW of installed capacity. It is estimated that the United States has a technically exploitable hydropower capacity of 1339 TWh per year, five times as great as current production However, it is not clear how much of this quantity is economically viable [144]. Based on economic criteria, the World Energy Council estimates that the United States could increase hydropower production by 50 to 100% [144]. Small hydropower systems in the United States have greater growth potential. Among systems less than 5 MW, 12 TWh were exploited in 2008 out of a potential of 198 TWh. [144]. The International Energy Agency estimates [59] that the world could produce 6000 TWh of hydropower in 2050 from a technical potential of 16,400 TWh.

Environmental and Social Impact

Like the economic impact, the environmental and social impacts of hydroelectricity are highly site specific, and it is difficult to generalize to all projects. Major impacts include the following:

- the damage to local ecology, particularly by impeding the flow of a river
- the climate impacts of the construction and operation of a dam
- the displacement of communities and agriculture through flooding
- the risk of a catastrophic failure.

A study of the Alborz dam in Iran found an external social cost of 16 ¢/kWh [134], mostly due to the impact on agriculture, though neither this nor any other individual study should be taken as representative of all dams.

In its 2011 assessment of renewable energy sources, the International Panel on Climate Change surveyed the literature on the life cycle impacts of hydroelectricity [77]. Most studies assess the impact of hydropower at 4-14 g-CO_2e/kWh, one of the most benign energy sources from a climate change perspective. However, some studies of reservoir hydropower place the life cycle impact as high as 150 g-CO_2e, due mainly to land use change. These effects include inundation of land, causing methane release from soil and vegetation decomposition, as well as release of greenhouse gases from silt at the decommissioning of the dam.

Due to the highly site-specific nature of hydropower, a blanket assessment of its merit and potential is not possible. Instead, each project must take into account the impact on the local ecology and population, along with the direct economic impact, before the project is undertaken [144].

5 Nuclear

Nuclear power is the extraction of energy from fission of heavy atomic nuclei. Here we assess the economic and environmental impact of today's nuclear technology and consider the prospects of future forms.

Today's Nuclear Economics

The U.S. Energy Information Agency estimates the price of a new nuclear plant constructed in 2020 at 9.5 ¢/kWh [36]. At this price, nuclear power is competitive in the United States with all other major forms of electric power except natural gas.

Like other non-fossil fuel energy sources, the cost of nuclear power is heavily weighted toward capital investment. Once the plant is built, it is relatively inexpensive to operate. However, nuclear financing presents special challenges. One factor is that plant lifetimes that are up to 60 years, as well as lengthy construction times, create a high risk of cost overruns [53]. The uncertainty is nuclear construction costs can be seen by variation by country and over time. The IEA Nuclear Energy Roadmap estimates overnight costs of about $3500/kW in China, $5500 in Europe, $5000 in the United States, and $4000 in Korea [62]. The World Nuclear Association has published information about the change in nuclear plant construction costs over time [146], driven by factors that include management issues, changes in safety regulation, and commodity prices.

Of the 9.5 ¢/kWh estimated cost of new nuclear power in the United States, an estimated 1.2 ¢ are spent on fixed O&M costs and 1.2 ¢ on variable O&M costs, including the uranium fuel cycle [36]. The fuel costs of a nuclear plant include the mining, processing, and enrichment of uranium, followed by fuel fabrication. The cost of the fuel cycle has been estimated at 0.66 ¢[146] or 0.79 ¢[101]. In the United States, nuclear plants are assessed at 0.1 ¢/kWh under the Nuclear Waste Policy Act for disposal of waste [147].

The challenging financing structures of a nuclear plant makes nuclear projects economically difficult. Under today's conditions, nuclear plants require some form of revenue certainty to be economically competitive [146]. Other policy options that would improve the economics of nuclear power include feed-in tariffs and carbon pricing. Another option is a capacity market, which arrange payments for dispatchable capacity to insure grid reliability [146]. The nuclear industry's long-term viability requires cost reduction.

Health and Environmental Impact

The 2005 ExternE survey of externalities of various power generation technologies [31] found a total of 0.31 ¢/kWh of external costs associated with nuclear power. Of these, at least 95% are upstream (mining and enrichment) or downstream (disposal) costs, with at most 5% pollution and other costs associated with the plant operation itself. Of the external cost of nuclear power, 70% stem from radioactivity. An earlier ExternE study [44] found a similar value at a zero discount rate and virtually no externality at a 3% discount rate. The OECD Nuclear Energy Agency study [109] reviewed other literature, most of which yields broadly similar estimates of nuclear externalities.

Catastrophic accidents, such as occurred at Three Mile Island, Chernobyl, and Fukushima Daiichi loom large in the public mind. However, including a factor of 20 for risk aversion and a multiplier of 1.25 based on macroeconomic analyses yields a cost of 0.017 ¢/kWh associated with the risk of a catastrophic accident [109].

Nuclear plants do not emit CO_2 directly, but their life-cycle operation brings an median estimated 12 g-CO_2e/kWh greenhouse gas emissions [123]. This figure is comparable to renewable electricity sources and far less than fossil fuels.

Though they are not trivial, it is important to keep perspective when considering the environmental costs of nuclear power. The 2005 ExternE figures places nuclear pollution damages at less than a fifth of natural gas and less than a twentieth of coal.

Small Modular Reactors

Small modular reactors (SMR), for which components could be mass-produced and assembled onsite, are one proposal to reduce capital costs and making nuclear power more attractive for smaller grids. SMRs bring about potential safety benefits that would reduce the likelihood of a the type of failure seen at Fukushima Daiichi in 2011. These include reduced need for backup power supply, improved seismic capability, and large underground pool storage for spent fuel [119].

There is great uncertainty about potential cost of future SMRs. Rosner and Goldberg [119] apply a 10% learning rate to capital costs and 2-3% for O&M costs, estimating that SMRs will achieve a levelized cost of electricity of 8 ¢/kWh once 18 modules, with capacity 1.8 GW, have been manufactured. The cost will decline to 6 ¢ once 54 modules have been manufactured. Achievement of these cost reductions will likely require some government support. If done through the Production Tax Credit, direct subsidy to SMRs will reach $600 million per year once all plants are operating [119]. Another estimate [1] is that a 45 MW SMR unit could generate electricity with an LCOE of 12.1 to 16.3 ¢(90% confidence interval, based on 16 expert judgments), while a 225 MW unit would cost 8.2 to 10.9 ¢. By comparison, a 1 GW light water reactor is estimated to cost 8.2 to 9.9 ¢. An estimate from Argonne National Lab [120] is that electricity from SMRs would have levelized cost from 5.5 to 9.7 ¢ as weighted average cost of capital ranges from 3% to 10%. The average of these estimates is 7.7 ¢/kWh.

Generation IV

The nuclear industry is developing a set of technologies which collectively are known as Generation IV. They are expected to be commercially available after 2030. The Generation IV Forum has identified six technology candidates [50]:

- gas-cooled fast reactors
- lead-cooled fast reactors
- molten salt reactors
- sodium-cooled fast reactors
- supercritical-water-cooled reactors
- very-high-temperature reactors.

According to an analysis from The Breakthrough Institute [100], the key drivers of cost reduction of future nuclear power are the following: safety, modularity, thermal efficiency, and technological readiness. Inherent safety allows cost reduction by making expensive containment systems and redundant power supplies unnecessary. Modularity allows efficient mass production. Conversely, the fuel cycle, waste management, and proliferation risk are minor components in nuclear system costs.

Among Generation IV concepts, high-temperature gas-cooled reactors are likely to be best suited for direct heat production for high-temperature industrial processes [100], an application for which effective low-carbon options are limited. Salt-cooled thermal reactors are a promising investment with commercialization possible in the mid-2020s. Supercritical water reactors are not very promising.

Fast reactors will generally require more development to reach commercialization. Sodium-cooled, lead-cooled, and molten salt fast reactors all show promise, but each must overcome significant technical hurdles. Gas-cooled fast reactors are less promising [100].

Cost estimates of Generation IV reactors are limited. Transatomic Power, which is developing a molten salt reactor, estimates that they will be able to produce power at 6.1 ¢/kWh [138].

Thorium

The thorium cycle is a proposed alternative to the traditional uranium cycle.

For use in existing light or heavy water reactors, the benefits of thorium are dubious. The IAEA estimates that a thorium fuel cycle will not produce savings compared to the uranium fuel cycle, for uranium prices up to about $300/kg [57], well above any price seen since 2008 [55]. At any rate, fuel costs account for a small portion of the total cost of electricity for a nuclear plants: about 0.66 ¢/kWh [146].

The real possibility of savings comes in next generation designs specifically constructed to take advantage of the properties of thorium fuel. A molten salt reactor could greatly reduce capital costs and costs by lowering reactor pressure, which would reduce the amount of concrete and steel needed for construction. One company, ThorCon, claims that their molten salt design will deliver power at 3.5 ¢/kWh by reducing material requirements, particularly of reinforced concrete, and by standardized modular construction [136]. However, the lack of recent demonstrative experience makes these claims uncertain.

6 Fusion

Fusion power operates by fusing light atoms, typically deuterium and tritium, into heavier atoms. This transformation converts a portion of the fuel's mass into energy, which a fusion plant then harvests. Fusion power promises cheap, stable energy production from a virtually unlimited fuel stock and with few environmental side effects. However, the technology has so far proven difficult to engineer and remains far from commercialization. There are several fusion technologies under development, including magnetic confinement and inertial confinement. In this section we explore pathways to commercial fusion power.

Today's flagship project in the development of magnetic confinement fusion is ITER, formerly the International Thermonuclear Experimental Reactor, due to begin operation around 2020 [43]. It is expected to be the first tokamak design to produce more energy than is required to sustain the reaction. According to the EFDA's fusion energy roadmap [43], this is to be followed by the experimental DEMO power plant around 2040, with commercial fusion power plants slated for operation around 2050.

The tokamak route does not come cheap. The estimated expense of the EU's research project from 2014-2030 is $16.3 billion, of which $6.2 billion will be devoted to ITER [43]. Beyond 2030 will be the additional expense of constructing and operating DEMO, as well as additional research needed to commercialize fusion power. Nevertheless, this expense is a small fraction of the potential value of low-cost fusion power to civilization. An estimated cost of fusion power, given the successful technical completion of the program, is 4-13 ¢/kWh [43].

In addition, even with full funding, the ITER pathway to fusion power is not guaranteed to succeed. There are several technical risks, chief among them the possibility that ITER's heat diversion strategy cannot be extrapolated to a full scale fusion plant. This would cause another delay of 10-20 years, and require the development of alternative strategies [43].

Another major approach to fusion energy is inertial fusion. An inertial fusion plant ignites a prepared fuel target with a laser, and thus the laser is the method of confinement. The National Academy of Sciences [20] analyzed the prospects of success of the inertial fusion program in the United States and developed a roadmap. There should be a single coordinated inertial fusion program, with "virtual laboratories" established to focus on three major technology tracks: laser, heavy-ion, and pulsed power systems. Eventually a choice would need to be made, as to which technology looks most promising for a demonstration plant. The estimated cost for this is $10 to $15 billion in capital expenses: upgrades to the National Ignition Facility, an Integrated Research Experiment, a Fusion Test Facility, and the demonstration plant. An additional $90 to $150 million per year is needed for research and other operations. Not given is a definitive estimate of the potential time until commercial fusion power is available [20].

Having failed to achieve ignition, the Laser Inertial Fusion Energy program at the National Ignition Facility was canceled in April 2014 [75]. Similar projects in inertial confinement fusion include HiPER [54] and Laser Mégajoule [81].

The American Security Project calls for $30 billion of investment in the United States in fusion energy research over a 10 year period [2], coordinated under a single fusion energy program with the Department of Energy.

Most of today's fusion research and development occurs in government-funded programs, but there are also several notable private sector fusion projects, including at

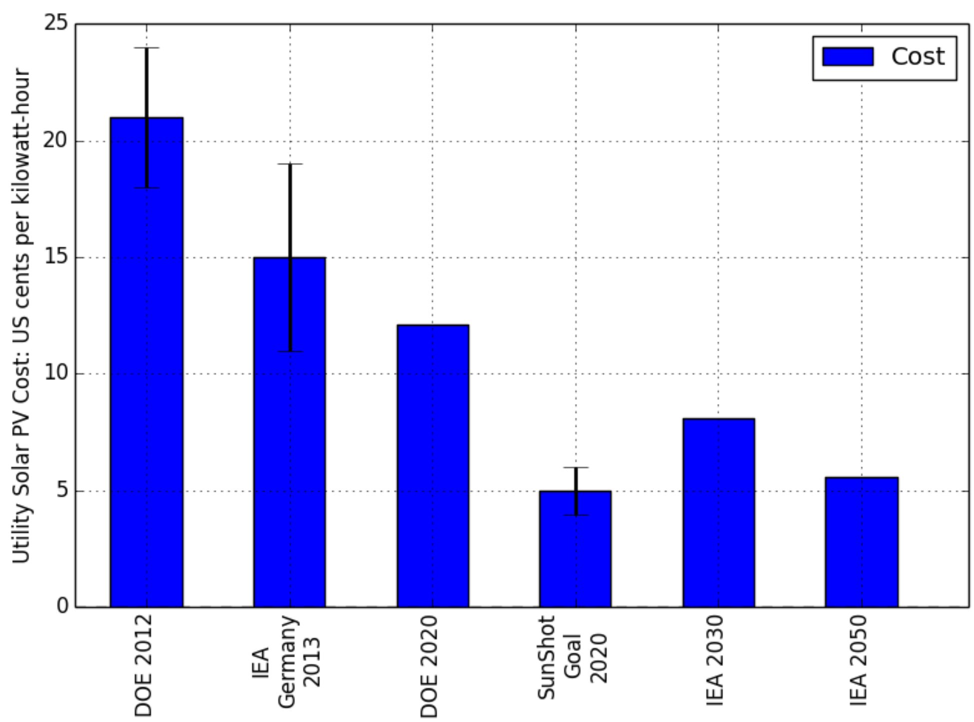
Lockheed Martin [87] and General Fusion [49]. These projects have encountered much skepticism [137].

7 Solar

Solar power is the direct conversion of radiation from the Sun into a usable energy form. Despite the difficulties, the potential is vast. Each year, the earth receives 885,000,000 terawatt-hours of energy in the form of sunlight [63], about 5800 times the 2013 world primary energy usage [14]. With 20% efficient solar cells and a performance ratio of 85%, collecting energy at an average global irradiance of 1825 kWh/m^2/year, the world's energy needs could be met with solar panels of an area the equivalent of a square 702 km on a side. This is 0.33% of the world's land area.

Photovoltaic Costs

Today solar energy is one of the most expensive forms available for electricity production, and considerable cost reductions are needed for solar to become economically viable without government support. The following chart shows recent costs of solar PV installations, the U. S. Department of Energy and the International Energy Agency's high-renewable future projections [63], and the goal of the U. S. Department of Energy SunShot program, which is that solar achieves grid parity of 6 ¢/kWh. Note that these figures do not include grid integration costs, which according to one estimate are about 1.5 ¢/kWh for solar [110], due primarily to its intermittent nature.



The IEA predicts gradual cost reduction at a learning rate of 18%. At this rate, at the target under the high-renewable scenario of 6600 GW by 2050, solar PV will have recently achieved decisive grid parity. The cumulative investment required to achieve this goal is \$7.8 trillion.

It is often claimed that solar PV has already achieved grid parity. This claim is based on an estimate of electricity costs by Lazard [82], which places solar PV at 7.2 to 8.6 ¢/kWh. We discount the Lazard study because its results are an outlier from other major studies of electricity costs, and Lazard provides no explanation for how the numbers were calculated, or why they are so much lower than either DOE or IAE estimates. For more information, see the comments by Alex Trembath at The Breakthrough Institute [139].

Nevertheless, in markets with particularly high solar irradiance, or high electricity prices, solar electricity is competitive with other sources. In 2015, Deutsche Bank estimated the unsubsidized price of rooftop solar electricity at 8-13 ¢/kWh [126]. The analysis estimates that solar electricity has achieved grid parity in half the countries surveyed, and in 14 U.S. states. The price threshold for grid parity is higher for residential installations, since these bypass the transmission and distribution costs of an electric grid. The grid constitutes about 40% of the price of retail electricity [126]. Extrapolating from recent history, the Deutsche Bank study anticipates higher electricity costs. This extends the range of grid parity and leads to 30% solar penetration by 2050.

As the price of solar cells decreases, the other costs of the system become more important. An October 2013 analysis [47] examined soft costs, which are all costs not directly related to hardware. They were found to be 64% for residential systems, and 57% and 52% for small and large commercial systems, respectively. The SunShot target for soft costs is 67 ¢/W for residential systems and 45 ¢/W for commercial systems [26]. In 2012, soft costs were \$3.42/W for residential systems and \$3.10/W and \$2.16/W for small and large commercial systems in 2012 [47]. The best short term potential for soft cost reduction is in business consolidation, which will streamline business and supply chain costs. Permitting does not add much monetary cost, but it can be a severe barrier to projects being completed at all [47].

A major barrier to large scale solar penetration is intermittency. Batteries to store solar energy are a solution, though today are too expensive to deploy on a large scale. The Deutsche Bank analysis [126] estimates the price of current battery technology at \$1500/kWh of storage capacity, which translates to an additional LCOE of 14 ¢/kWh on a solar installation. The analysis estimates a price reduction to \$150/kWh within five years, or an LCOE of 2 ¢/kWh, driven by price reductions in lithium-ion batteries.

Environmental Impacts

While solar electricity generation does not emit greenhouse gases directly, the full lifecycle emissions are estimated at a median value of 41 g-CO_2e/kWh for rooftop and 48 g-CO_2e for utility solar [123]. This is about 0.19 to 0.22 ¢/kWh at a carbon price of \$45/ton. While greater than emissions for wind and nuclear power, these figures are far less than for any fossil fuel source.

Land use is a significant cost of solar power. The total area taken by solar arrays ranges from 2.8 to 5.5 acres/GWh/year for photovoltaic systems and 3.2 to 5.5 acres/GWh/year for concentrated solar power (CSP) systems [106]. Among PV systems, concentrated PV requires the least land due to the feasibility of higher efficiency cells (discussed below), and larger arrays tend to be more land-efficient than smaller arrays. Among CSP systems, tower systems are the most land-efficient.

The manufacture of solar cells requires toxic heavy metals and can generate pollution. These effects vary considerably depending on the technology and the standards employed in the manufacturing process [95].

Advanced Solar Cells

Despite the impressive reduction in solar cell costs in recent years, solar PV electricity remains expensive. The SunShot Vision study [26] outlines a program for solar grid parity in the United States by 2020. The study recognizes that their aggressive cost reduction goals will probably require commercialization of new technologies. Since the cells themselves are now a small portion of the cost of a solar installation, with other system costs constituting the majority, the most important advances in solar cell technology revolve around improved efficiency. This reduces system costs on a per-kWh basis.

Solar cells are generally divided into three generations. Today, the most commonly produced cells are first generation mono-crystalline or multi-crystalline silicon cells (sc-Si or mc-Si) [68]. Despite their commercial maturity, further cost reductions may be possible via economies of scale and improved manufacturing processes, as noted above.

Second generation cells are at the early phases of commercialization and still have small market shares. Based on thin-film PV technology, these cells include amorphous or micro-morphous silicon (a-Si or μc-Si), cadmium-telluride (CdTe), copper-indium-selenide (CIS), or Copper-Indium-Gallium-Selenide (CIGS) compositions. While a-Si or μc-Si cells potentially require less money and material to manufacture, they suffer from lower efficiency (up to 12.2% in the laboratory) and higher rates of degradation [68]. Multi-junction thin film silicon cells, which are design to harvest red and infrared light, can have an additional 10% improvement to efficiency [68]. CdTe and CIS/CIGS cells have shown efficiencies up to 16.7% and 20.3% respectively [68].

There are several models of third generation cells, although they are still in the research and development phase and have significant hurdles to overcome before reaching commercialization. Challenges include durability, resistance to water, and the discovery of economical manufacturing methods. Dye-sensitized solar cells use a dye molecule for charge separation, and are the closest approximation among solar technologies to photosynthesis. The advantage of DSSC is their low potential manufacturing cost, but they suffer from lifespan issues and low efficiencies [68]. Improvements in these areas are active areas of research. Organic solar cells are also inexpensive but suffer from low efficiencies (only 6-8% in the laboratory) and short lifespans. Nevertheless, their flexibility might make them particularly suitable for portable electronics and residential installations. Finally, advanced cells based on quantum dots, quantum wells, and super lattices have the potential for high efficiencies and use in concentrating PV systems, though they are in early stages of development [68].

Solar Thermal

A solar thermal plant concentrates sunlight for the production of heat. The heat can then be used, either directly for industrial applications or to boil water and spin a turbine to generate electricity.

At the end of 2013, the world had installed 3.6 GW of solar thermal electricity, over 80% of it since 2009 [64]. There are several CSP models, including linear Fresnel reflectors, central receivers on a tower, parabolic dishes, and parabolic troughs [64]. Modern CSP plants include thermal storage, often in the form of a molten salt, which can last for several hours and reduce unexpected intermittency.

As is the case with photovoltaics, solar thermal costs vary by climate. Recent plants in the United States and Morocco both are estimated to have generated electricity at 19 ¢/kWh [64]. The IEA roadmap projects that solar thermal will reach 980 GW of install capacity by 2050 and a price of 7.1 ¢[64]. Interest in solar thermal has diminished somewhat due to the decrease in the price of PV systems, thereby slightly moderating the projected growth. This target will require a total investment of $4.3 trillion.

In addition to producing electricity, a solar thermal plant can be used for hydrogen production and for generating high-temperature process heat or steam for industrial processes.

The life cycle emissions of solar thermal are slightly better than for conventional solar power, estimated at 27 g-CO_2e/kWh [123].

Concentrating PV

Concentrating PV (CPV) is a method of solar energy capture in which an optical device concentrates sunlight at a rate of anywhere from 2-1200 suns onto a photovoltaic cell. Due to the high concentration, the economics favor higher efficiencies even at the cost of more expensive cells. Multijunction cells, which harvest a larger portion of the solar spectrum, may achieve efficiencies as high as 50% [68].

There are two major classes of CPV under development. High concentration, 400-sun or greater, is used primarily with multijunction cells. The major challenges of high concentration CPV are reliability of optics and the tracking system, as well as the longevity of cells under high concentration [78]. Medium concentration systems, between 3 and 400 suns, are more often based on silicon cells, though with geometries and other modifications designed for CPV systems [78]. An advantage of CPV, especially high-concentration CPV, is that the higher cell efficiency reduces the land area required.

A 2015 analysis [114] has shown promising development in the cost of CPV systems. System prices range from $1600-2400/kW. The LCOE is 11-16 ¢/kWh where the direct normal irradiance (DNI) is 2000 kWh/m^{2}a (kilowatt-hours per square meter per year). At the world's best sites with a DNI of 2500 kWh/m^{2}a, the LCOE is 9-13 ¢. This has been achieved after a modest 330 MW cumulative installation. It is projected that by 2030, CPV could reach an LCOE of 5.0 to 8.3 ¢, with the lowest prices achieved at high DNI sites, and installed costs could reach $800-1200/kW [114]. These prices undercut conventional PV power plants at that time. A challenge to a large-scale CPV industry is the availability of germanium for III-V multijunction cell production; it is not clear how much world germanium production can be expanded and at what cost [114].

Luminescent Solar Concentrators

A luminescent solar concentrator (LSC) is a flat device that collects solar energy and redirects it to a solar cell. The surface contains luminophores, which absorb high frequency light and re-emit it at a low frequency. Much of the re-emitted light remains in the waveguide, the material that transmits light to a solar cell. Candidates for luminescent material include organic dyes, quantum dots, and rare earth minerals [86], or a hybrid material might be the best solution [121]. Unlike traditional solar collectors, an LSC can function with diffuse sunlight. This allows harvesting of energy on cloudy days, dispensing of tracking systems, and reduction in the intermittency problem [121]. The technology is still in the research phase. If it is found to be commercially viable, LSC has potential application in building integration and could replace silicon panels for residential and commercial installations. The biggest challenge in developing LSC is developing a luminophore that contains the following desired properties [121]:

- absorbs the full solar spectrum
- does not reabsorb light emitted from another luminophore
- re-emits with high efficiency
- long lasting.

Due to the precommercial status of LSC, we are unable to confidently assess its ultimate economic viability. Nevertheless, the potential for lower cost solar power with reduced intermittency and ease of deployment in urban environments is sufficiently attractive to warrant further research and development.

Space-based Solar Power

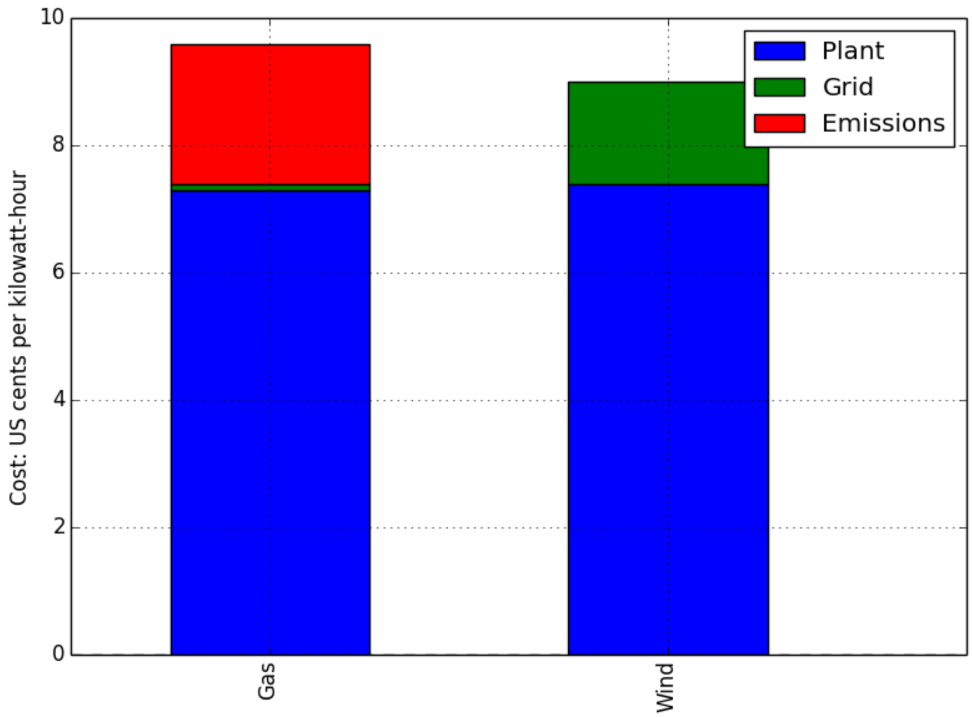
Space-based solar power (SBSP) is a proposed system that harvests solar energy from satellites in geosynchronous orbit. The satellites transit the power to a ground rectanna in the form of microwaves. A 2007 study [99] found that SBSP is fully within the realm of technical feasibility, though its economic feasibility is another matter. A proof-of-concept demonstration could be launched in a 4-to-6 year period at a cost of $5 to $10 billion [99]. The SBSP study group called for a research program on the scale of the fusion energy program or the International Space Station [99], on the order of tens of billions of dollars. A successful SBSP program would be a very lengthy and expensive undertaking, and it has the potential to provide cheap, clean, and reliable power from an unlimited source. Such a program makes most sense in the context of a larger space development program [99], and evaluation of such a program is beyond the scope of this analysis.

8 Wind

After decades of development, wind power is the most advanced renewable energy source. As of 2013, the world had installed 320 GW of cumulative wind capacity and produced 628 TWh of wind electricity, or 2.7% of all electricity [14].

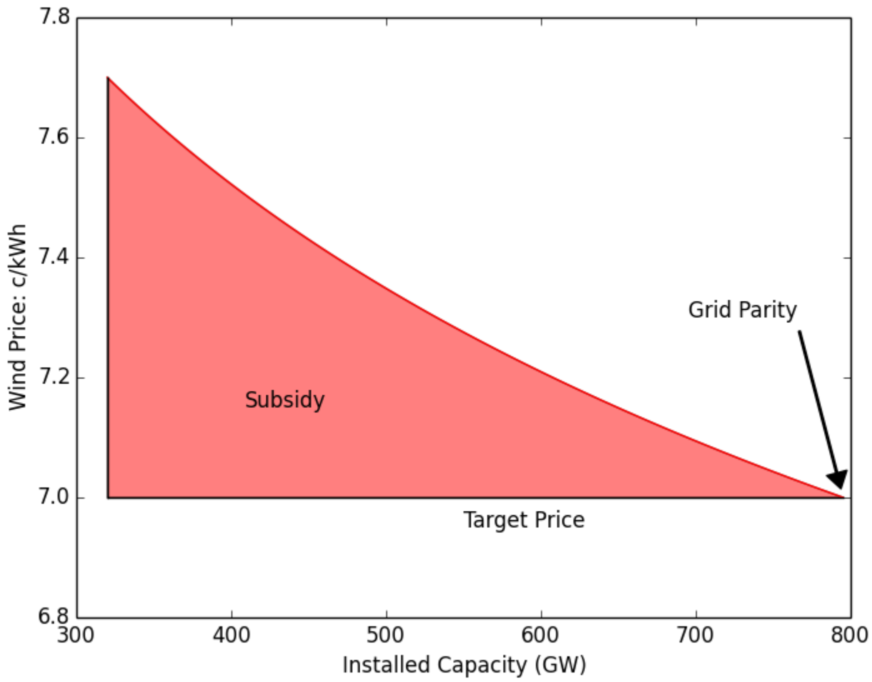
Wind Energy Cost

The following illustrates the cost of wind power in the United States, together with the lowest cost competitor, natural gas. The plant-level costs, which include both capital expense, fuel, and other operating expenses, are taken from Energy Information Administration's 2014 Annual Energy Outlook [36], while system effects, including the costs of connecting the plant to the grid and of dealing with intermittency, are taken from OECD Nuclear Energy Agency. The system cost of wind assumes that wind comprises 10% of electricity generation. CO_2 emissions are assigned a \$45/ton cost [56], with emission values taken from the IPCC [123].



In order for wind to decisively undercut natural gas in price, taking system effects into account, the cost of wind power should be reduced to at least 5 ¢/kWh. To consider how that might happen, suppose that the cost of wind decreases with a 7% learning rate [69] [70], which applies both to capital and operating expenses. In order to achieve the 5 ¢ goal, a total of 19.8 TW of wind capacity must be installed. This would exceed the world's electricity production and not be realistic.

With the above carbon pricing, the target price for wind is 7 ¢/kWh. Then 795 GW of installed capacity would be needed. Following is an illustration of the cost reduction that comes from "learning by doing" and the subsidy needed to reach the competitive price.



Using a present cost of \$2000/kW, and ignoring O&M costs, a worldwide investment of about \$900 billion in wind energy construction is needed to achieve this cost reduction. If the market price for the electricity is 7 ¢/kWh, then \$36 billion of this investment would be needed in the form of subsidies, and the rest could be provided by the private sector.

Due to the low learning rate, the above analysis is highly dependent on initial assumptions, and the numbers should be taken as order of magnitude estimates only. Due to the variance in the quality of wind resources and the prevailing price of electricity, private investment may be enough to drive cost reductions in some markets. This would reduce the government subsidy required to achieve wind cost reductions, but it could increase the time.

The IEA's Wind Energy Technology Roadmap, also using a 7% learning rate, projects a 25% cost reduction in capital costs and a 23% reduction in O&M costs by 2050. This would reduce wind power costs to 5.9 ¢/kWh [65].

For intermittent resources such as wind, system effect costs grow with the proportion of installed capacity, and thus present a diseconomy of scale. Given the limited potential for cost reduction below 6 ¢/kWh, for wind power to supply the majority of the world's electricity, system effects must be reduced through technologies such as grid-level storage. Give these challenges, we do not expect wind energy to play a big role in liberalized markets except in regions with particularly good wind resources.

Environmental Considerations

From a global warming perspective, wind power among the most benign energy sources. Onshore wind has a lifecycle greenhouse gas emission impact of 11 g-CO_2e/kWh, while the impact of offshore wind is 12 g-CO_2e [123].

Wind farms also impact habitat. When considering spacing, about one acre per megawatt is permanently disturbed by a wind farm [140]. Wind turbines also kill birds and bats in their operations, though this problem is manageable [140].

Offshore Wind

Placing wind turbines offshore, either on a lake or off an ocean coast, has several advantages. The wind tends to be stronger and more reliable offshore, and in some areas, the water might be the only available real estate. However, the challenges of engineering structures in the water add to the cost. The U.S. Energy Information Agency estimates that an offshore wind farm coming online in 2019 will generate electricity at a cost of 17.5 ¢/kWh [36], far from a competitive level.

The offshore wind resource is substantial. A 2010 Department of Energy analysis [124] found that the United States has 4150 GW of offshore wind capacity, in excess of current American usage. Of this, about 2451 GW are in deep water, greater than 60 meters, and 1071 GW are in shallow water, less than 30 meters. Waters less than 3 nautical miles from the shore contain only 580 GW of offshore wind resource, while 2696 GW are 12-50 nautical miles from shore. Deeper and farther sites present greater logistical challenges. The world offshore wind resource is estimated at 192,800 TWh [4], far in excess of current world electricity usage.

Significant cost reductions are needed to make offshore wind a viable energy source. A 2012 UK task force estimated that, with improvements in supply chain management, standardization and testing, contracting, regulation, transmission, and finance, the price of offshore wind could be reduced to 16 ¢/kWh in 2020 [105]. An October 2008 estimate by the Carbon Trust was more optimistic: at a 13% learning rate, a levelized cost of electricity of 12 ¢ could be achieved by 2030 [17]. This would require significant policy support, including $6-8.5 billion of global R&D, much of which would be private. It should be noted that under the aggressive expansion of offshore wind contemplated in the Carbon Trust's analysis, the R&D yields $28 billion of savings in capital costs. The most important research area is in turbine foundations, as they represent a major source of offshore wind cost, and more advanced foundations are needed to harvest the abundant deepwater resources. An additional 1 ¢ of balancing cost is predicted if wind penetration reaches 30% of UK electricity [17]. A May 2012 study by The Crown Estate [22] saw offshore wind projects to be decided in 2020 as having costs ranging from 14.2 to 18.4 ¢, depending on the pace of technical innovation and supply chain improvement. In the rapid innovation scenario, with a cost of 14.2 ¢, 43 GW of offshore wind are installed in Europe. A survey by PD Ports [113] of the offshore wind industry in the UK found that executives expect the price to decline to 17 ¢ for projects with a final investment decision in 2023. The average of these estimates is 15.8 ¢/kWh.

Like onshore wind turbines, offshore turbines have an impact on wildlife and the natural environment. Their installation and operation can kill birds, bats, and marine animals [111]. We have not attempted to quantify these costs in monetary terms.

In the most optimistic policy scenario modeled by the National Renewable Energy Laboratory, offshore wind covers only 1.1% of the world's electricity market in 2095 [4]. The above survey of the cost reduction potential of offshore wind, centered on the industry in the UK, does not give much reason for optimism that offshore wind energy will be economically viable without government support in the foreseeable future. Only radical technological innovations would drive the cost to an economically viable level.

High Altitude Wind

Wind speeds increase with altitude, which is why taller wind turbines and turbines mounted on hills tend to be more effective. Ground-based wind systems are limited by the practicality of building tall turbines. In principle, a system that could harness the winds of the jetstream, kilometers above the ground, could be very powerful. Several systems are under development to do just that, by flying turbines with kites. High altitude wind is less intermittent than wind near the ground, and the ability to adjust the height of a turbine would further reduce intermittency [3].

There is no consensus on the magnitude of the resource available. A 2009 study by Archer and Caldeira [3] found that a device density of 1 m^2 per km^3, roughly enough to power all of the world's energy needs today, would have negligible impact on the climate. Much higher densities would be possible, though with climate impacts of cooler temperatures, greater sea ice extent, and less precipitation. Miller, Gans, and Kleidon in 2011 estimated the jetstream potential resource at 7.5 TW, less than half of today's world energy use, yet harvesting all of it would cause severe climate disruption [93]. This estimate is based on an analysis of the energy sources that sustain the jetstream (the pressure gradient and the Coriolis force) rather than what is contained in the jetstream itself. While we suspect the smaller value is closer to the true potential, more research is needed to gain a confident assessment of the high altitude wind potential and climate risk.

Several startups are working on high altitude wind projects [130], though the industry is far from commercialization. A bottom-up estimate suggests that the levelized cost of high altitude wind electricity could be as low as 2.5 ¢/kWh [118], with the savings over conventional wind realized by accessing the valuable high altitude resource. However, it is impossible to place any confidence in cost estimates, given the immature state of the industry. Another uncertain factor is the risk of an accident, should a tether break and a floating turbine crash. Nevertheless, high altitude wind shows enough potential that it is worthy of public support. Important areas include financing for pilot projects and further research into the resource base and potential environmental consequences. Governments should also consider how pilot projects can be safely permitted. It is premature to discuss a route to commercialization before the feasibility of the technology is proven.

9 Geothermal

Geothermal energy is the extraction of heat from below the Earth's surface for energy. Hot reservoirs can be used for electricity production, while warm reservoirs can be harvested directly for heat for industrial processes or district heating.

Resource Potential and Environmental Considerations

In 2013, the world had installed 11,709 MW of geothermal capacity, led by the United States (3442 MW), the Philippines (1868 MW), and Indonesia (1339 MW) [14].

Krewitt et al. [76] estimate a potential for geothermal energy, excluding enhanced geothermal systems, by 2050, given anticipated technological advancement. It is 1.5 TW, or 45 EJ/year, for electricity, and the direct heat potential is 1040 EJ/year. These figures are approximately 50% of 2013 electricity consumption [14] and 650% of 2008 heat consumption [76]. This estimate assumes drilling to depths up to 10 km, which is today's state of the art [135].

The IPCC [123] estimates the lifecycle greenhouse gas emissions of geothermal energy at 38 g-CO_2e/kWh, comparable with other renewable energy sources and a cost to society of 0.2 ¢/kWh when emissions are priced at $45/ton. The Geothermal Energy Association notes that emissions vary by technology: flash geothermal plants produce 180 g-CO_2e/kWh, dry steam plants produce 27 g-CO_2e, and binary plants produce 5.7 g-CO_2e [90].

An additional advantage to geothermal power is the minimal land use required [90].

Potential Cost

Today, the most developed form of geothermal energy is hydrothermal. Although highly site-specific, it is currently the cheapest mainstream electricity source at 4.8 ¢/kWh [36]. The IEA Geothermal Roadmap estimates hydrothermal electricity at 5-8 ¢[61]. The major elements of the capital cost of a geothermal plant are construction of the plant itself and production well drilling. These are 47% and 37% of the capital cost respectively [21]. The IEA Geothermal Roadmap [61] predicts that flash hydrothermal plants can continue to decrease in cost at a learning rate of 5%, leading to about a 0.25 ¢/kWh cost reduction by 2050.

Although the resource base is greater, binary geothermal technology is not as developed as hydrothermal. The IEA estimates electricity produced from binary plants at 6-11 ¢/kWh, though ranging as high as 12 ¢ in the United States and 21 ¢ in Europe [61]. By 2050, the roadmap envisions that binary plants will decrease in cost to 5-8.5 ¢.

Enhanced Geothermal

An enhanced geothermal system (EGS) extracts heat from deep within the Earth and in environments that are not naturally porous. Unlike traditional hydrothermal geothermal energy, EGS resources are accessible from almost everywhere on Earth, though at varying cost and difficulty.

Vast resources are potentially available with EGS. Blackwell et al. [12] estimate a theoretical resource of 13,300,000 EJ in the United States. Of this, an estimated 2%, or 266,000 EJ, could technically be recovered [135], far more that could conceivably be needed. For use in electricity production, it is estimated [98] that 4 TW, or 31,300 TWh/year, could be harnessed in the United States. This exceeds current world electricity consumption [14].

EGS technology does not face any obvious technical barrier and is currently undergoing demonstration deployment, notably at Cooper Basin in Australia [6]. Nevertheless, additional deployment is needed in order to reduce the cost.

Today's EGS cost is hard to state precisely due to the immature nature of the industry. Estimates range from 10 to 31 ¢/kWh [61], depending on economic conditions and the physical characteristics of the site. The lower bound refers to a 300°C site at 4 km, which are ideal conditions.

The MIT study [135] estimates that electricity produced from EGS will be competitive without further subsidy at only about 100 MW of deployment. This requires a cumulative $920 million to $1.14 billion of investment, of which $340 million to $460 million must be provided through subsidy. At this point EGS electricity will reach 7 ¢/kWh. Price reduction will be driven by technology and learning improvements. After about 5000 MW of deployment, costs will start to increase due to the fact that the best EGS sites will already be utilized. The study estimates that 50 years after deployment, 100 GW could be deployed in the United States, reaching a price of just over 8 ¢/kWh. If prices for natural gas or other electricity sources remain low, then such large-scale EGS deployment will not happen without accelerated cost reductions.

More recent work by Beckers et al. [9] confirms the high potential of EGS technology. For medium- and high-grade resources, the costs of EGS electricity could reach 7.1 and 4.6 ¢/kWh respectively by 2030. Medium-grade resources are widespread in the Western United States and are available in other parts of the country as well. The potential for EGS heat is even greater. For low-temperature industrial processes such as paper processing and biomass drying, direct heat could be provided for $5.5/MMBTU, $4.0/MMBTU, and $3.5/MMBTU from low-, medium-, and high-grade EGS sources, respectively. Even for low-grade resources, which are available almost everywhere, EGS heat can undercut natural gas prices.

Another possible application of EGS technology is in district heating. Commercially mature EGS technology could provide district heating from a medium-grade resource for about $10/MMBTU [116], highly competitive with average U.S. residential natural gas prices since 2005 [25]. The higher heating prices reflect the fact that, due to the seasonable variation in district heating needs, not all of the extracted geothermal heat would be used. Further cost reductions may be possible through combined district heating and cooling systems.

10 Wave

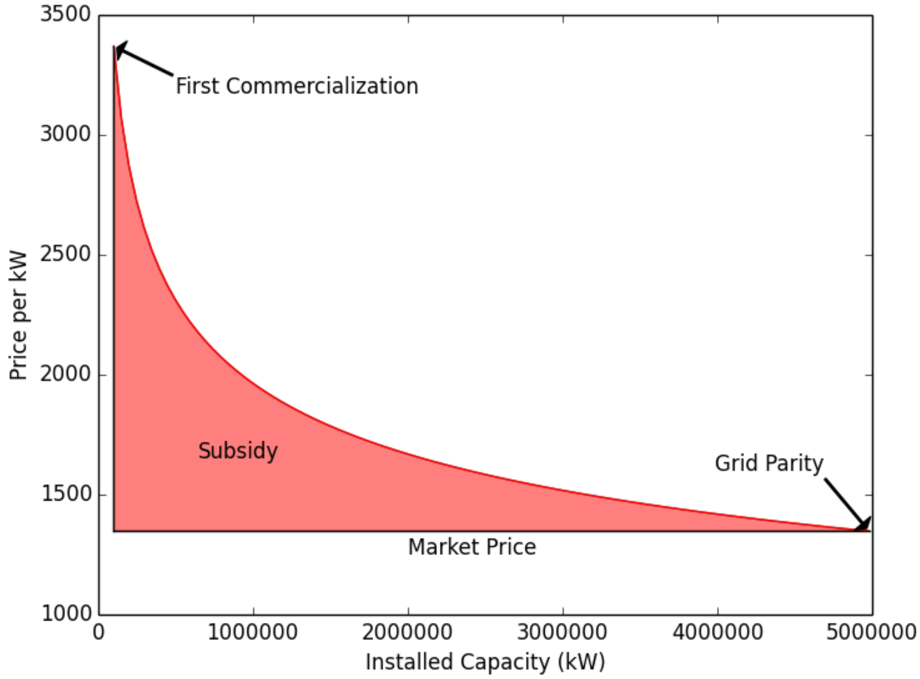
Wave power functions by converting the kinetic energy of ocean waves into electricity. The technology holds considerable potential but is not yet commercialized. In this section, we discuss a route to commercialization and the benefits that would result.

Pathway to Commercialization

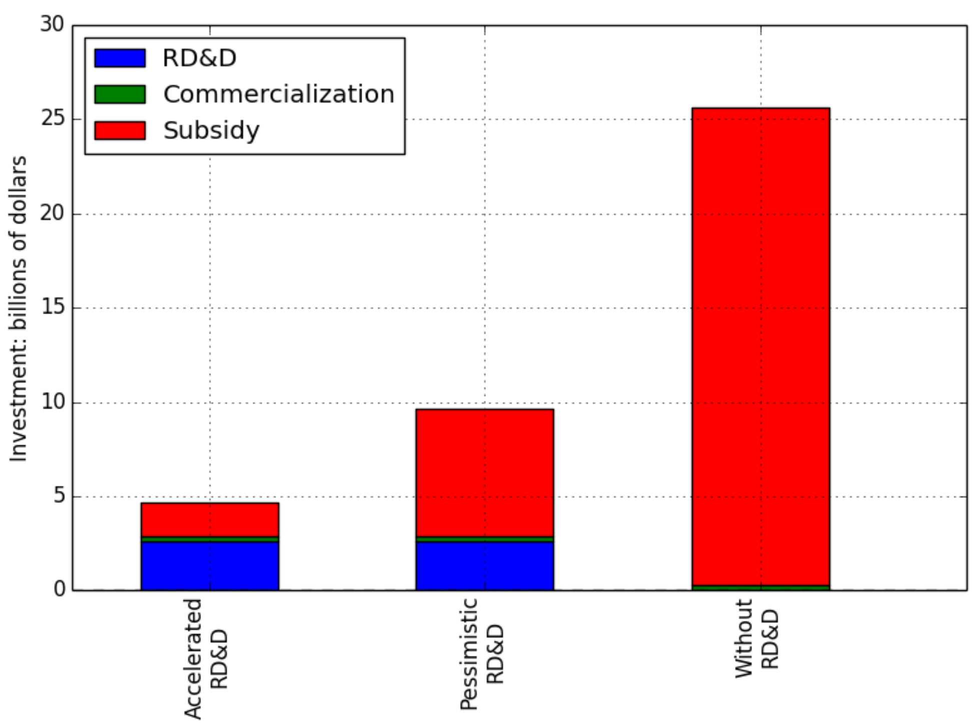
Of all today's commercially mature energy production technologies, wind energy is the most similar to wave energy, as both derive power through the kinetic energy of a fluid. The U. S. Department of Energy spent $2.5 billion in research in wind energy from 1978 through 2014 (see [18] and [23]), and today wind energy is beginning to achieve commercial viability without subsidy.

In addition to research, an estimated $300 million of investment are needed to bring partial scale projects to full commercial scale [104].

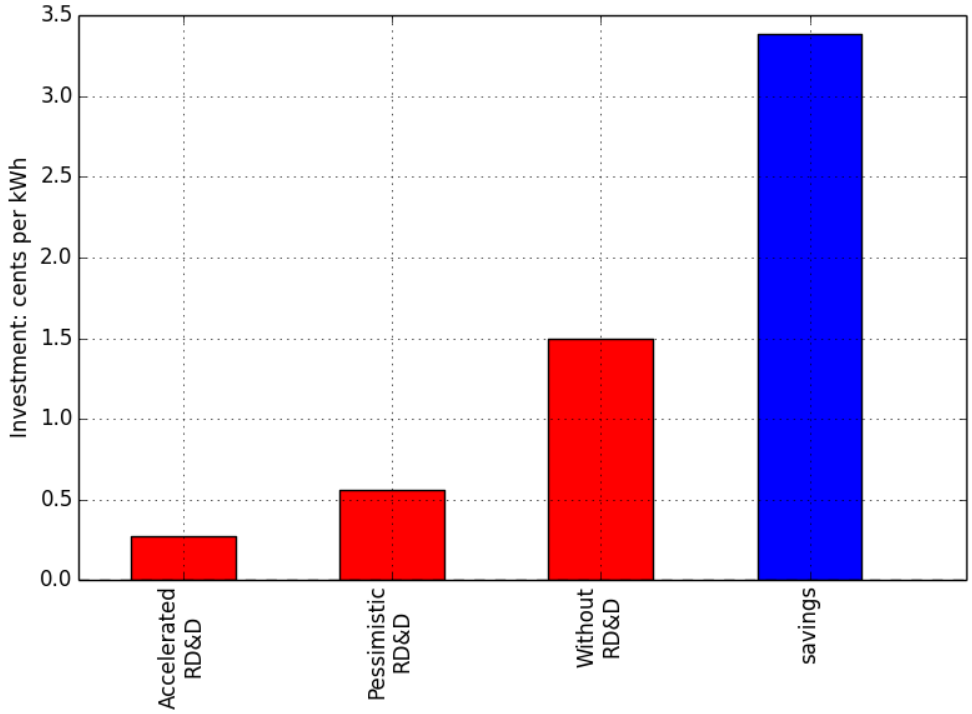
According to estimates from RE Vision Consulting [115], if wave energy was commercialized in its state as of 2012, it would cost 28 ¢/kWh. If an accelerated research, development, and deployment was conducted, then this initial commercial cost could be reduced to 15 ¢. In either case, price reductions proceed with a 15% learning rate. RE Vision Consulting estimates 30% uncertainty in the opening cost, and so in the pessimistic case, an opening cost of 20 ¢ is assumed. At a sufficient amount of installation, the price of wave power should achieve grid parity of 6 ¢. The amount of subsidy required reflects the difference between the actual price of wave energy and the prevailing price of electricity until grid parity is achieved. The needed subsidy is shown as the area of the shaded region in the following illustration.



Following is an illustration of the total investment, in the form of accelerated research and development, commercialization, and subsidy that is required to bring wave power to grid parity.



Following is an illustration of the above investment amounts as a share of the amount of electricity the US wave industry could ultimately generate, together with the savings that result from wave power undercutting other sources in coastal areas.



The Continental United States has an estimated wave energy potential of 359 TWh/yr (see [24], page 17). This energy is assumed to be available ten years after full commercialization of wave energy, and it is valued at a discount rate of 8% per year for 20 years thereafter. The second chart illustrates the investments costs in cents per kilowatt-hour of the (discounted) electricity that wave power could ultimately produce.

If the learning rate of 15% holds until 147 GW of wave energy have been installed (at 30% capacity, 95% availability, and 98% transmission efficiency), then the levelized cost of electricity of wave energy should decrease to 2.7 ¢/kWh, reflecting a 3.3 ¢ savings over the baseline electricity price. The bottom line is that, under the accelerated R&D scenario, the research, development, and deployment ultimately costs about 0.25 ¢/kWh, and the savings are over 3 ¢/kWh.

A 2008 review of wave and tidal technology [131] projects that wave power could eventually reach a price of 4-6 ¢/kWh. Though more that given above, this analysis confirms the potential for wave power to undercut existing forms of electricity generation. This is based on a learning rate of 14%.

Environmental Considerations

Like all energy sources, the life cycle of wave power includes some emissions of greenhouse gases and other pollutants. The life cycle CO_2 emissions are estimated at 13.2 g-CO_2e/kWh, mostly from manufacturing of the devices [131], with a potential for reduction as the technology matures. The manufacture of wave energy devices generates small amounts of other pollutants [131].

More research is needed on the impact of wave energy capture devices on marine wildlife. One potential benefit is that the devices could serve as artificial reefs, while a potential drawback is the negative impact of noise and electromagnetic fields on wildlife [28].

An additional factor to take into account in the deployment of wave energy is competition for other sea uses, such as shipping and fishing.

11 Marine and Hydrokinetic

Marine and hydrokinetic (MHK) power refers to a form of power generation that harnesses the kinetic energy of water, though it is generally considered separate from hydropower. We discussed wave energy in the previous section, and in this section we will evaluate several other forms of MHK.

Tidal Power

Tidal power harnesses the kinetic energy of water induced by tides. It is estimated that the United States has a potential for 50 GW of power generated from tidal stream, or the flow of water through narrow inlets [51]. The vast majority of this resource (47 GW) is in Alaska. Siemens [128] estimates the world tidal capacity at 120 GW, though acknowledges high uncertainty. This contrasts to a world electricity installation of about 5550 GW in 2012 [35].

The tidal industry has been slow to develop, due in part to engineering challenges that have been greater than expected. The UK Carbon Trust in 2011 estimated [16] the price of tidal power in the UK at 46 to 53 ¢/kWh, far from economically viable. As more tidal stream devices are installed, there is significant potential for cost reduction due to learning effects at the following learning rates: 12% for the structure and prime mover, 13% for the power takeoff system, 12% for station-keeping, 2% for the grid connection, 15% for installation, and 18% for O&M [16]. Deploying today's technology and reducing cost through learning-by-doing would yield a cost of 24 ¢ by 2050, with 12.5 GW of tidal power deployed [16]. This is still prohibitively expensive. Under accelerated innovation, tidal power could be below 16 ¢ by 2050 with 12.5 GW deployed.

A recent analysis estimates the potential cost of tidal stream power in the UK at 8-12 ¢/kWh [37]. Geenhouse gas emissions are low. The IPCC estimates lifecycle emissions at 1 g-CO_2e/kWh for tidal current and 6 g-CO_2e/kWh for tidal range [83].

Ocean Thermal

During the day, the sun heats the upper layers of the ocean, creating a temperature differential between the surface and the ocean depths. An ocean thermal device (OTEC) harnesses this differential for energy production. A closed design uses a heat exchanger to evaporate another fluid and push a turbine via the Rankine cycle or the Kalina cycle. An open design pumps the warm water into a vacuum chamber and flash evaporates it. There are variations on the design, though not yet any widely commercialized technology. Another possibility is simply to harvest the cool water for a district cooling system.

Estimates vary on the world's OTEC capacity. One study [88] places a technical resource at 6.3 TW, or 55,000 TWh per year, though this does not take into account economic feasibility. This resource is concentrated in tropical and subtropical waters. In the United States Exclusive Economic Zone, the resource is 530 GW, potentially producing 4636 TWh of electricity each year. Much of this resource is in the vicinity of small island possessions of the United States, and greatly exceeds the local need. To fully harness the American OTEC resource, it is necessary to either capture and store the energy for transport, or use it for local industries that presently do not exist. A 2014 estimate [71] holds that OTEC could supply all of the world's electricity needs without disrupting the temperature profile of the oceans.

A 2001 analysis [89] found that the initial OTEC plants will be very expensive, on the order of $15,500 to $31,000 per kW. Like most other renewable energy systems, OTEC has high capital costs and low operating costs compared to fossil fuel generation. With maturity, floating plants on the scale of 50-100 MW could cost $7750/kW, still quite expensive. These high costs could be offset by coproducts. An open or hybrid OTEC cycle would use a steam condenser to harvest fresh water. An OTEC system used for air conditioning might be more economical than a system used for electricity production [89]. Cold water harvested from the deep ocean might also support the tropical agriculture of crops that are otherwise only suited for cooler climates [89]. Another potential coproduct of OTEC is open-ocean mariculture, fed by nutrient rich water pumped from the deep ocean [89].

In a 2014 assessment, the International Renewable Energy Agency [71] identified the cost of small OTEC systems, under 10 MW, at $16,400 to $35,400 per kW. This is economically feasible in small island communities with high electricity costs, if the OTEC plant generates economically useful coproducts. Larger scale installed OTEC plants might range from $5000 to $15000 per kW, while floating plants might cost as little as $2500/kW, yielding an LCOE of 7-19 ¢/kWh. This requires large scale deployment and a steep learning curve. Due to the limited number of projects thus far, none of which exceed one megawatt in capacity, these figures are highly uncertain [71]. The cost also depends on the choice between open and closed designs. While an open design is projected to be more expensive ($11700/kW versus $9100/kW for a 50 MW project), the possibility of fresh water production from an open design may justify the cost [142]. Like all capital-intensive projects, the economic feasibility of OTEC is highly dependent on interest rates.

The environmental impacts of OTEC are expected to be benign [89], with the main impacts the release of CO_2 (though in quantities comparable with other renewable energy sources) and the risk of the leakage of working fluids. One estimate is that life cycle emissions from OTEC are 28 g-CO_2e/kWh [7].

River Current

River current power harnesses the kinetic energy of water flowing in a river. River current differs from hydroelectric power, in that no dam is used to build a reservoir or impede the flow of water.

The Electric Power Research Institute [32] estimates that the Continental United States has a technical river current resource of 120 TWh per year, though the practical recoverable resources might be considerably less. Of this value, 57 TWh/year could be recovered from the lower Mississippi River and 21 TWh/year in Alaska. This is still less than 3% of United States electricity production, and for that reason we have chosen not to evaluate the economic potential of investment in river current power.

Osmotic Power

An osmotic, or salinity-gradient, power plant harvests the potential energy in the pressure difference between fresh and salt water, where fresh water rivers meet the ocean. This is done by placing a membrane where the two water types meet, and allowing the hydrostatic pressure between them to push a turbine. An osmotic power plant runs at nearly full capacity and could serve as reliable base load power. The technology is relatively new, with the first demonstration plant opened by the Norwegian company Statkraft in 2009 [52]. About 0.7 to 0.75 kWh of energy is dissipated when a cubic meter of fresh water mixes with the ocean. Harnessing this energy from all the world's rivers could potentially yield 1650 TWh per year of energy production [52], about 7% of the world's electricity use in 2013 [14]. Another estimate [132] is of a technical resource of 5200 TWh/year of osmotic power, of which 520 TWh/year could be recovered when ecological constraints are taken into account.

Improvements in membrane technology, driven by the water desalination industry, have improved prospects for osmotic power in recent years. The industry expectation is that a membrane power density of 5 W/m^2 is needed to make osmotic power profitable, and this has been achieved by several designs in the laboratory [52]. A low cost membrane with density 5 W/m^2 could allow osmotic power to be produced at 7-13 ¢/kWh [52].

The environmental impact is generally expected to be low compared to fossil fuel plants, though limited research has been done; the main concerns revolve around eutrophication, water temperature changes, and discharge of chemicals [52].

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