Article 4: Economics

Understanding the economic potential of fusion energy is a complex challenge since fusion is still many years from being a market option. Uncertainties abound at multiple scales, from the power plant to the full global energy system.

This article has two parts. In the first part, we consider the determinants of the cost of electricity from an individual fusion power plant. In the second part, we investigate how fusion will compete for energy market share. We limit our discussion to magnetic confinement fusion, and more particularly to its tokamak configuration.

Estimates of the cost of fusion electricity

The cost of fusion electricity is driven principally by its capital cost and by how many hours the plant can run each year. Quantitative discussion focuses on "the levelized cost of electricity." In essence, the levelized cost is the total cost of building a plant and running it over its lifetime, divided by the kilowatt hours of energy that the plant produces over its lifetime. Like its fission counterpart, the total cost of a fusion power plant is dominated by its initial capital costs. The kilowatt hours produced over its lifetime are affected primarily by the size of the plant, the number of hours that it is able to run each year, and the efficiency with which the thermal energy produced through fusion is converted into electricity.

There are many estimates of the capital cost of a fusion plant *[1,2,3,4]*. The estimates range from \$2,700 to \$9,700 per kilowatt of capacity. The plants have a capacity between 1,000 and 1,500 megawatts. Assuming that the capital cost per kilowatt is roughly independent of the size across this small range of sizes, the estimated capital cost of a fusion power plant with 1,000 megawatts of capacity would range from 2.7 to 9.7 billion dollars. (Costs throughout this article are in 2010 US dollars *[5]*).

The wide range of capital costs is partially explained by varying assumptions about how many plants of the same kind have been built prior to the plant whose cost is being estimated. Fusion plants are expected to become less expensive as more plants of a specific design are built. "Technological learning" captures this issue: cost models often assume that costs will fall at some well-defined rate as additional units of the same kind are installed.

The wide range of costs is also due to differences in the assumed technological maturity of the plant. Fusion plants are likely to become less expensive as they incorporate successive advances in technology. For example, with maturity may come greater efficiency in converting the thermal energy of fusion into electricity. Nearly a factor of two is at stake, with conversion efficiency ranging between 30 and 60 percent. This efficiency depends especially on the temperature of the blanket; the blanket absorbs the thermal energy released in the fusion reactions and delivers most of that thermal energy to the turbine that produces electricity. The larger the difference between the temperature of the blanket and the temperature of the environment (ocean or river water, for example), the higher the efficiency of electricity generation. Efficiencies of 30 percent are representative when the blanket is water-cooled and maintained at a temperature of 300 degrees Celsius, so that steam enters the steam turbine at nearly 300 degrees Celsius. The higher 60 percent efficiency might be realized if a blanket could be maintained at much higher temperatures as a result of being cooled by a gas or a liquid metal.

Two kinds of costs are associated with any power plant: the capital cost for building the plant (incurred in its first years) and the cost of running it (for many further years). To combine these costs into a complete cost per year that can be used to calculate cost of electricity requires "annualizing" the initial capital cost, meaning transforming it into a cost per year to match the units of the costs of running the plant. Typically, this is done by multiplying the capital cost by some factor (in units of percent per year). A typical multiplier is 15 percent per year, which not only transforms the capital cost into a cost per year, but also incorporates the associated costs of borrowing money, depreciation, insurance, and taxes. Using this multiplier, if the capital cost for building a 1,000 megawatt plant is six billion dollars, the annualized cost will be 900 million dollars per year, or 900 dollars per year per kilowatt of plant capacity. If the plant were to operate continuously over all the 8,760 hours in a year, the cost per kilowatt-hour associated with the capital cost alone would be approximately ten cents.

However, plants do not run continuously for a whole year; if the plant ran only half the year, the capital component of the cost per kilowatt-hour would be twenty cents. Accordingly, another source of variation in cost estimates is the assumption about the number of hours that the plant runs each year. A capital-intensive technology like fusion generally requires nearly full-time operation to be competitive. Unique in its significance for fusion plants is "scheduled component replacement," which will affect its availability. Critical components degrade and need to be replaced many times over the lifetime of the plant as a result of the wear and tear that they sustain from irradiation by fusion neutrons and charged particles.

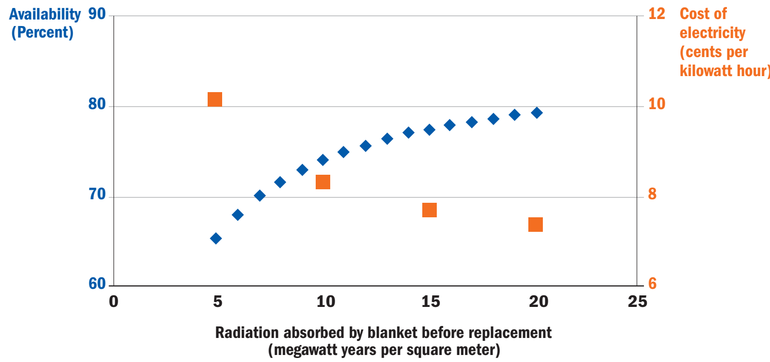

Figure 4.1: The dependence of fusion power plant availability and the cost of fusion electricity on the durability of the fusion blanket *[7]*. The durability of the blanket is quantified as the maximum amount of absorbed radiation (in megawatt-years) that the blanket can tolerate per square meter of blanket surface area. The more radiation the blanket can absorb before replacement, the fewer the periods during which the power plant is shut down for blanket replacement and the lower the cost of electricity.

Accordingly, the fusion research community pays close attention to the replacement of parts that lose their function after only a few years. The most important areas of the plant, from the perspective of durability, are those in close proximity to the fusion plasma itself, notably the first wall, the blanket, and the divertor. One current estimate indicates that divertor replacement could take four months and divertor replacement in combination with blanket replacement could take six months. Every replacement would also require a one-month cooling period at the front end and a one-month conditioning period at the back end before the plant could produce power *[6]*.

Thus, there is an important relationship between durability of components requiring replacement and the cost of fusion electricity. Figure 4.1 shows the benefit obtained when a blanket is able to withstand a larger amount of radiation before replacement. Consider the durability of the blanket for two values of the total tolerable neutron absorption before blanket replacement is required: five and 20 megawatt-years of absorption of neutron irradiation per square meter of surface. This four-fold increase in durability is seen to produce an increase in power plant availability from 65 percent to 80 percent and a fall in the total cost of a kilowatt-hour from ten cents to seven cents. The cost curve has diminishing returns: at high durability, further blanket durability has diminishing benefit, as other factors (such as divertor replacement) become the more important causes of shutdowns.

A priority for fusion, therefore, is the development and demonstration of materials that will tolerate the fusion environment for a long period. The development of analogous materials has enabled a well-operated fission plant to run roughly 90 percent of the time, with a single shutdown period roughly once a year. The most difficult component to replace in a fission plant, the pressure vessel within which the fissions occur, is expected to remain intact for the lifetime of the plant. However, the neutrons from fusion are more energetic than those from fission and do more damage.

Figure 4.2 shows the allocation of the total cost of fusion power reported in the European Power Plant Conceptual Study *[1]*. A similar analysis is found in the U.S. Advanced Research, Innovation, and Evaluation Study *[2]*. The European study investigates four variants of fusion plants, but only Model A, the variant described as requiring the least amount of new technology, is shown in Figure 4.2. The cost estimates are based on a "tenth of a kind" plant, meaning that these are the costs for the tenth plant of a similar kind – lower costs than the costs for the first plant because some technological learning has occurred. The capital cost is estimated to be $9,700 per kilowatt of capacity, the discount rate is 6 percent, there is no taxation, the plant lifespan is 40 years, the plant is expected to run 75 percent of the time, and efficiency of conversion of fusion power to electricity is 31 percent.

With these assumptions total costs can be grouped, and shares for each group can be estimated: Capital (73 percent), Divertor Replacement (12 percent), Blanket/First Wall Replacement (4 percent), and Operation and Maintenance (9 percent). Note that the combined cost for the replacement of the divertor and the blanket's first wall is 16 percent of the total cost. Other costs, mainly the costs of fuel and decommissioning, are reported as being negligible. The cost of handling the regenerated tritium is presumably placed in the Operation and Maintenance category, since it is a recurrent cost. The same study reports that the largest contributions to the total capital cost are 1) the combined cost of the magnets and cooling system, and 2) the combined cost of buildings and site preparation.

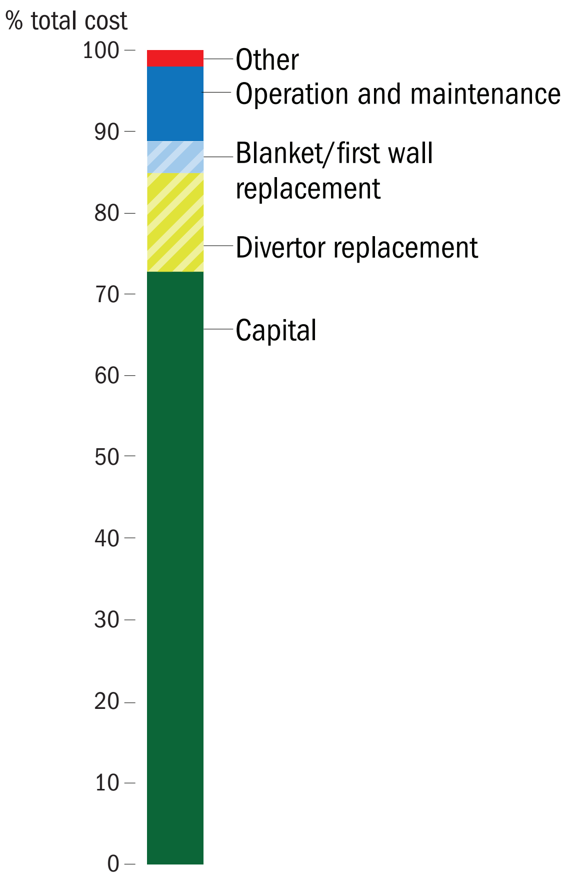

Figure 4.2: Components of the total cost of electricity produced by a fusion power plant based on a tokamak reactor, shown as a percent of total cost *[1]*.

We draw five key messages from this section:

1. There is a wide range of estimates for the cost of electricity from future fusion power plants.
2. Uncertainty regarding in what directions and how rapidly technology will advance is a key contributor to this range.
3. For all these estimates the primary determinants of the cost of electricity are capital costs and the proportion of time that the plant can operate.
4. Capital costs are dominated by the costs of the magnets and cooling system.
5. The proportion of time a plant can operate is mainly determined by how often the first wall, blanket, and divertor need to be replaced.

While higher-level modeling of fusion energy's future economic competitiveness (such as the market share study described immediately below) can provide an orientation to fusion's potential role in the global energy system, the deep uncertainty about fusion's likely future cost implies that all quantitative economic estimates emerging from these models are highly speculative at this stage.

Fusion's market share in the 21st century

The prospects for fusion energy as a source of electricity over the coming century will depend not only on fusion's own future costs but also on the future global electricity market. The size of that market depends on the rate of economic growth, the amount of electrification of the energy system, and the efficiency with which electricity is used to provide goods and services. Since fusion is a low-carbon energy source, its future role in the market also depends on the extent to which concern for climate change is translated into carbon policies that disadvantage high carbon energy sources (the fossil fuels: coal, oil, and gas) relative to low-carbon sources. Also significant are the costs of other low-carbon sources relative to the cost of fusion.

Little modeling of the impact of fusion on energy markets has been done, largely because cost estimates for fusion are so uncertain, as demonstrated in the previous section of this article. We report one of the few modeling studies where fusion costs and related economic parameters (such as the time of fusion's arrival) are assumed and fusion's impact on the full global energy system is developed *[8,9]*. We provide quantitative results from this study that illustrate some of the factors that can influence fusion's future market share. The exact model results are unimportant relative to its qualitative conclusions, which are consistent with other work *[3,10,11,12]*.

The researchers used one of the best-known integrated assessment models, known as GCAM, developed and maintained at the Pacific Northwest National Laboratory of the U.S. Department of Energy. The model's inputs include the performance of the economy, carbon-cycle science, climate policy, and the costs of competing energy technologies. Its outputs are representations of future energy markets in 14 geopolitical regions every five years from 2015 to 2095. At each time step, the demand for electricity is met by a broad array of energy technologies.

Although the model can describe the entire energy system, here we focus on the electricity sector, where the model calculates electricity prices, carbon prices (carbon taxes), and electricity demand. The study we are reporting adds fusion to the list of electricity-generating competitors that GCAM has modeled previously. The key assumptions for fusion power are the following:

1. *Timing* The model's base case assumes that the first fusion power plant becomes available in 2035, at least ten plants are operating in 2050, and at least 100 plants are on line in 2065. This ambitious schedule is hard to reconcile with the current schedule for ITER and follow-on research projects (see Article 6).
2. *Cost* The median capital costs fall as fusion deployment grows over time. The capital cost of the initial plant is $6,000 per kilowatt of capacity, which is within the range of capital cost estimates discussed above. The unit cost is assumed to fall as additional units are built, as may be appropriate for an immature technology. The unit cost in 2065 is $3,800 per kilowatt, and costs continue to fall moderately after that.
3. *Availability* The plant is assumed to run 90 percent of the time. This would require that the plants achieve shorter shutdown periods for the replacement of irradiated reactor components than is currently expected (see the first part of this article).

The overall optimism in these assumptions suggests that these GCAM model runs probably overestimate the market share of fusion at various future dates. However, the qualitative results from these model runs are instructive, especially those that reveal the dependence of fusion's market share on alternative policy environments. These results reveal the importance of the assumed costs for two of fusion's main low-carbon competitors: carbon dioxide capture and storage (CCS) and nuclear fission. They also show the strong dependence of fusion market share on the price imposed on carbon dioxide emissions to the atmosphere.

In CCS power plants, a fossil fuel or biomass is burned and the carbon dioxide emissions from combustion are "captured" – prevented from escaping to the atmosphere. The carbon dioxide is then "stored," typically, deep below ground in a porous saline geological formation. The first CCS plants are now running. GCAM allows alternative constraints to be placed on the maximum amount of carbon dioxide storage space available below ground in each geopolitical region.

As for fission, its median capital cost for the baseline case in 2065 is $2,700 per kilowatt, about 30 percent less than the corresponding 2065 capital cost for fusion. An alternative in the model is a "low" fission case where in 2095 fission is more expensive (about 30 percent more expensive than the baseline case), which closes the gap between the costs of fission and fusion.

GCAM, for all cases, also restricts the contributions of wind power and solar power to reflect their intermittency.

Fusion competes with 14 other electricity production technologies to meet electricity demand. Three options are carbon-emissions-intensive: power from coal, natural gas, and oil without CCS. The other 11 options are low-carbon – low-carbon rather than zero-carbon because of the carbon dioxide emissions associated with construction of the plant and other ancillary factors. Biomass-based electricity without CCS is one of these. Another four are CCS options, differing in their fuel: coal, natural gas, oil, and biomass. The remaining six are nuclear fission, geothermal energy, hydropower, wind, ground-based solar, and rooftop solar. The market shares of all 15 production technologies from 1990 to 2095 are shown in Figure 4.3 for two representative GCAM scenarios (the original study explores many more scenarios).

Panel I shows Scenario I, the base case and the point of departure for the analysis. Circumstances are unfavorable for fusion because there is no climate policy (no carbon price); all of fusion's competitors, including fission, have their baseline costs; and (not actually relevant, because without a carbon price CCS cannot be viable) there is ample space below ground to store carbon dioxide. Efficiency in electricity use has limited impact: global electricity demand, which in 2010 was approximately 22 trillion kilowatt-hours (a trillion is a million million, or 10^{12}), rises to 90 trillion kilowatt-hours, more than four times the 2010 value, in 2095. Coal power dominates electricity supply in 2095 with 29 percent market share, followed by natural gas and nuclear fission, each with 18 percent. The shares of wind and ground-based solar are seven and five percent respectively. Fusion's share is four percent, or four trillion kilowatt-hours.

How many fusion power plants would be operating in 2095 in Scenario I if fusion actually were to produce four trillion kilowatt-hours that year? Assuming a representative plant that has a capacity of 1,000 megawatts (one million kilowatts) and runs 8,000 hours per year (approximately 90 percent of the time), the plant would produce eight billion kilowatt-hours each year. Thus, the answer is that approximately 500 fusion plants would be operating in 2095 in Scenario I. This is approximately the scale of nuclear fission power today.

Panel II presents Scenario II, a far more favorable case for fusion, where there is significant climate policy, a cost penalty for nuclear fission, and limits on available carbon dioxide storage space. Climate policy is assumed to take the form of a concentration of

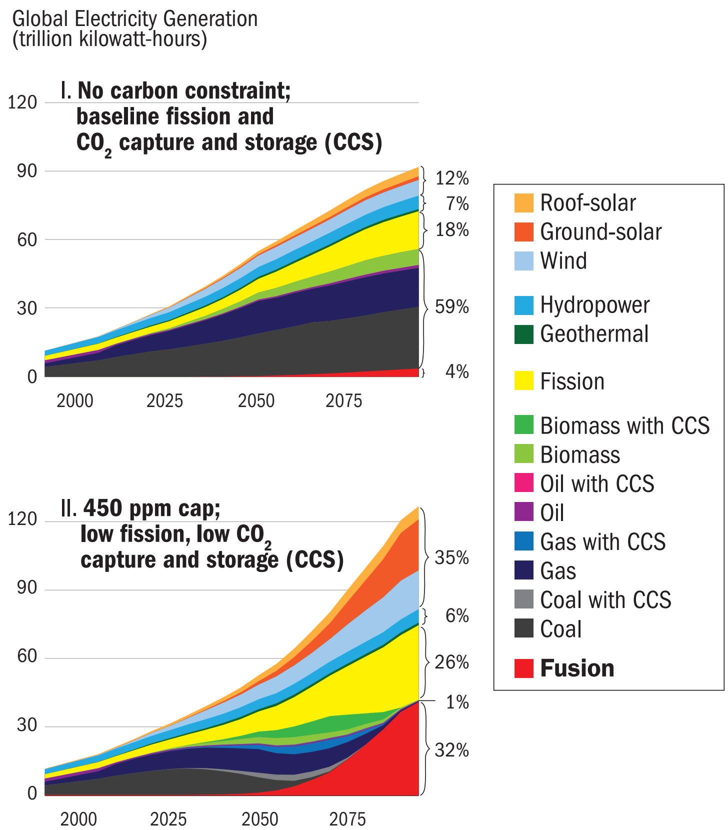

Figure 4.3: Production of global electricity in the 21st century, by source, when fusion is an option *[8]. Panel I (above):* Scenario I, a case unfavorable to fusion because there is no carbon policy and both fission and carbon dioxide capture and storage (CCS) options are fully available. *Panel II (below):* Scenario II, a case favorable to fusion because there is a 450 parts per million (ppm) climate target and fission and CCS options are constrained. The numbers at the right (in percent) are the shares of total electricity production in 2095 for five bracketed power sources; from top to bottom, these are intermittent renewables, non-intermittent renewables, nuclear fission, fossil sources with and without CCS, and nuclear fusion.

carbon dioxide in the atmosphere not to be exceeded at the end of the century. Within GCAM there is a carbon cycle model which links carbon dioxide concentrations to carbon dioxide emissions and thereby limits emissions. Emissions reductions are achieved by a globally uniform price on carbon dioxide emissions, which improves the competitiveness of low-carbon energy relative to fossil fuels.

In Scenario II the global energy system is constrained by the requirement that the maximum carbon dioxide concentration in the atmosphere must never exceed 450 parts per million (ppm). (When the concentration is 450 ppm, 450 carbon dioxide molecules are present in every million molecules of air.) This constraint is one of the most common climate policy objectives in the modeling literature *[13]*. A 450 ppm cap is estimated to have a 50 percent chance of limiting the rise of the average surface temperature of the Earth to two degrees Celsius relative to its temperature 200 years ago, thereby potentially avoiding some of the dangerous impacts of climate change. The current concentration is already about 400 ppm. By comparison, the carbon dioxide concentration in 2095 for Scenario I is 810 ppm, roughly double the concentration today. Scenario I assumes that no climate policy is enacted; specifically, throughout the 21st century there is no price on carbon dioxide emissions to the atmosphere. By contrast, in Scenario II a carbon price is imposed that grows throughout the century and reaches more than $280 per ton of carbon dioxide in 2095.

Comparing Scenarios I and II reveals that total electricity demand in 2095 is even higher in Scenario II than in Scenario I. Global electricity consumption in 2095 is 120 trillion kilowatt hours for the 450 ppm climate target, versus 90 trillion kilowatt hours when there is no climate target. The climate target pushes the energy system toward electricity and away from the direct use of fuel – for example, toward electric vehicles and electric space heating.

Fusion's market share in 2095 is eight times larger in Scenario II (32 percent) than in Scenario I (four percent). In Scenario II fusion is the dominant supplier of electricity in 2095, providing 41 trillion kilowatt hours, or ten times as much electricity as in Scenario I. Since we estimated that the fusion output in Scenario I would require 500 representative fusion power plants, it follows that in Scenario II 5,000 of these plants would be operating.

But the differences between the scenarios extend well beyond fusion. Electricity from fossil fuels and biomass provides 59 percent of global electricity when there is no carbon policy, but only one percent when a 450 ppm target is met. In the presence of the climate target, fusion, intermittent renewables, and fission all increase their market share to make up the difference, gaining 28, 23, and 8 percentage points of market share respectively. The gain in fission's share happens in spite of its higher cost in Scenario II than in Scenario I. Scenario I never uses CCS technologies, because there is no price on carbon.

In Scenario II, CCS versions of biomass power plants and (to a lesser extent) natural gas power plants play a significant role in the middle of the century but by 2095 they no longer contribute, presumably because carbon dioxide storage costs have risen as the regional storage sites have filled up.

In summary, as with any similar study, the results reported here are strongly dependent on the assumptions. The results are sensitive to the date of the first commercial plant and its initial cost, the rate of fall of unit cost through learning, and the competitors' costs and constraints. Notably, the costs of fission and fusion are assumed to be similar. Nonetheless two of the study's results are broadly relevant. First, without a carbon target and in the absence of any explicit penalties on fusion's competitors, fusion's share of electricity at the end of the century is small, if it competes at all. Second, the combination of a carbon target and restraints on fission and CCS increases fusion's market share dramatically.

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