Biofuels, particularly from algae

I have done studies on alternative energies, going back to 1980, and also on growth and resource use of photosynthetic organisms, including ordinary plants and algae. Here is a critique based on my knowledge.

The attractions of biofuels are several:
1) Renewability
2) Domestic production, vs. importation
3) Possible carbon neutrality
4) Avoidance of emission of some other important pollutants, esp. mercury

The problems of biofuels are also several:
1) Huge demand for land area → habitat loss, and possibly increased CO_2 emissions
2) Possibly large water use (for field crops)
3) Intensiveness of capital, both monetary capital and embodied energy → long payback times
4) Low net energy return (quite variable by type of biofuel) → ditto
5) Considerable inputs of fertilizer, esp. nitrogen-based
6) Miscellany, including possible catastrophic loss to pathogens, temperature extremes

Getting to some details:

The attractions:

Renewability: no question here. Biological systems renew themselves. Algae are particularly simple – one can harvest any amount, and the remainder of the stock will grow back to any desired density

Domestic production: they can be grown almost anywhere that the climate allows. Many areas of the US qualify for growing field crops for biofuels (corn, sorghum, switchgrass); these crops can go dormant or be reseeded and need not be winter-active or even winter-hardy. Southern regions of the US hold promise for algae, with the limitation that the culture can't be allowed to freeze. Heating is very expensive and seriously reduces the net energy yield, so that siting is very important.

Possible carbon neutrality: Burning any fuel emits CO_2 to the air, with attendant contributions to climate change. Regrowing the crop recaptures CO_2 in a sustainable cycle. Carbon neutrality is not guaranteed, however. Some ethanol-from-corn plants are directly net CO_2 emitters, when they use coal combustion for process heat and distillation (incredible choice). Other such plants are net CO_2 emitters in the large, if forested land is cleared to start the crop, as in Amazonia.

Avoidance of emission of some other important pollutants: coal is the dirtiest fuel imaginable, as it contains mercury in significant amounts, as well as sulfur. Biofuels contain no more than background levels of such pollutants, so that burning them causes little impact. Nitrogen oxides form in any combustion, but these are controllable in vehicles with catalytic converters. At powerplants, the picture is mixed.

The problems:

Huge demand for land area: My expertise, from long and varied research, is in photosynthesis and other resource use by plants, from the basic photophysics of how chlorophyll captures and transfers energy, to how the whole system works at the global scale. Simple fact: photosynthesis has a low energy efficiency. There are very good reasons for this, including metabolism required to make organisms self-maintaining / self-repairing and also the drop in atmospheric CO_2 over millions of years that plants themselves caused by being partly rot-resistant and thus causing the burial of huge amounts of carbon.

Normal green plants capture energy in light, using about 120 photons to make one molecule of glucose sugar. The energy in the photons is more than 4 times larger than the energy captured in making sugar, so that the efficiency of capturing energy in sunlight is less than 25% at best. That's in the initial steps. The plant then has to use part of the energy in sugars to make other things – proteins, fats, etc., and also to remake damaged parts. The highest efficiency attained in field crops is 6% over a season in sugar cane. The average efficiency is more like 2%. For the globe as a whole, it is 0.3%, because of dormant seasons, etc. Algae are no better than land plants. However, they can be grown in contained cultures that use high levels of CO_2, such as in power-plant exhaust (oops – that means taking up mercury and such if it's a coal-fired plant). They might hit 6% on a continuing basis.

What does this mean for land use? The other consideration is that sunlight is a dilute resource. We can hit 1 kW per square meter at high noon here, but the average is about 180 W per square meter (W m^{-2}), accounting for day and night, winter and summer, clear and cloudy conditions. So, at 6% efficiency in capturing energy, algae might average 10 or 11 W m^{-2}. That's as raw biomass. They have to be processed, and drying either is really slow (using more sun and more land, or, worse, using some of the energy provided by the rest of the crop). If the system hits 60% efficiency in going from raw biomass energy to final electric or fuel energy, we're getting about 6.5 W m^{-2}. Now let's say we want to replace a typical 1000-MW power plant, which actually consumes about 2500 MW of thermal (fuel) power, converting it at only 40% efficiency. This is 2.5 billion watts. We will need about 0.4 billion square meters. This is 400 square kilometers, or over 150 square miles. Of course, you don't have to make one big plant, but the total area of many smaller plants has to be this large.

There are much better ways of using land, even cheap land. Solar cells, or photovoltaics, easily hit 11% efficiency, and new ones, not yet commercial, are exceeding 15%. Let's say that 13% is a decent figure for plants that will be built. This is 13% from sun to electricity – no other conversion inefficiencies. This gives us $0.13 * 180$ W $m^{-2} = 23.4$ W m^{-2}. To get 1000 MW of power, we still need a large area, almost 43 million square meters. This is 43 square kilometers or about 16 square miles…slightly more than 10% of what the algal pond would take. Solar thermal power is about as efficient. Both technologies are proven to a high level. I attended the American Geophysical Union meetings in 2007 and 2008 and the recent Energy Summit in the Sandias. The reality is that these technologies have only a short way to go to large-scale commercialization. They are far ahead of algal biofuels. They don't readily make liquid fuels for transportation, but they have a clear role in the energy economy. They could even be pushed, with some conversion losses, to make liquid fuels, as by making hydrogen gas from electricity to combine with CO_2 in the air, generating alcohols and then hydrocarbons.

Possibly large water use: Certainly, field crops use a great deal of water. This is a physiological necessity that absolutely cannot be altered. Some gains in what we term water-use efficiency are possible, but they are marginal. It takes about 500 masses (pounds, kilos, whatever) of water to make one mass of plant matter. I have done theory and experiments on this.

Algae can be used in closed systems, with only minimal water loss. Some can also grow well in brackish water. These plusses are balanced against some minuses. First, closing the system means that the containment vessel has to be built. This is expensive in both dollars and materials. The materials cost a significant amount of energy to make and deploy. (The same is true of, say, photovoltaic cells, but their energy payback is only 1.5 to 2 years, in a 20 to 30 year lifetime…a bargain). Second, the standing volume of water is large. A reasonable depth for growth is at least 0.5 meter or about 1.5 feet. Let's go back to that algal pond that replaces a 1000-MW power plant (and that needs such a traditional plant nearby, to get high efficiency, by growing at high CO_2). The area is 400 million square meters, so the volume is 200 million cubic meters. This is about 7.2 billion cubic feet, or 54 billion gallons, or about 1.65 million acre-feet. We don't have this to spare in fresh water, so we'd go to brackish water. We do have a lot of this. We'd have to be careful not to spill much of it and salinize the land. We'd also have to reuse it very thoroughly. This is where my knowledge is nearing its limit. The water does accumulate metabolic byproducts of the algae, which have to be removed. I'm not sure how readily this is done by purification vs. partial disposal.

Intensiveness of capital, both monetary capital and embodied energy: This has been brought up in the other topics above. Containment vessels are costly, in both dollars and energy. Let's say that the vessel is polycarbonate (it has to be strong and tough, resistant to impact), and that it's about ¼" or 6 mm thick, and on top and bottom, for a total of about ½" or 12 mm. I haven't done detailed calculations on the energy it takes to make this plastic, nor on dollar costs for purchases in volume. I'll make a preliminary estimate here. The embodied energy (energy needed to manufacture an item, including the energy value left in the product as a potential combustible fuel) in plastic is likely to be at least 3 times the energy in the same amount of hydrocarbons, which is about 40 kJ per gram. It is 1.2 times as dense as water, so that it weighs about 1200 kg per cubic meter. This huge pond container has 400 million square meters x 0.012 m depth, or 4.8 million cubic meters of polycarbonate, weighing about 5.8 million tons (5.8 trillion grams). The embodied energy, at 120 kJ per gram, is about 7×10^{17} Joules (J, or watt-seconds). A MW-year is 3.1×10^{13} J. Thus, it takes about 22,000 MW-years of energy. The 1,000-MW plant pays back its energy cost in 22 years! No viable commercial plant can bear this. The payback time has to be far less than half the useful lifetime.

Low net energy return: This has been outlined above, in discussing embodied energy and other topics, so there's no need to belabor it, other than adding one more energy debit: operational costs. Here, I'm not including the cost of processing final algal biomass to fuel, but only the cost of stirring the tanks, cleaning the water, etc. Algal ponds must be stirred in order to keep high photosynthetic efficiency: algae get light-saturated at light levels far below full sunlight. They'd drop to efficiencies well below the 6% I cited earlier. If one stirs the culture, this brings up algae that were deeper down and light-starved. The net effect is to average out the light level and keep the photosynthetic efficiency high. The cost of stirring is something I haven't determined, but it is significant – stirring must be maintained at least all day.

Considerable inputs of fertilizer: organisms need mineral nutrients to grow, in addition to their use of water, light, and CO_2. The most costly nutrient to provide, in dollars and in energy to produce fertilizer forms, is nitrogen. Ammonia manufacture for fertilizer consumes 3% of world energy currently. For high-value food crops, the cost is sustainable by farmers, if only in more developed nations or subsidized regions. For fuel, which is worth much less per mass, the cost of this input is very high. There are some cyanobacteria that fix nitrogen from the air and that might be co-cultured with true algae. This can be tricky. There is also the possibility of recovering a substantial amount of the nitrogen in the algal biomass, if the whole organisms are not dried and burned as fuel. Of course, if the whole organism is not used – say, only 40% that is lipid (oil) – a very generous figure, then this reduces the efficiency of algal growth for fuel even more and increases the land use and water use.

Miscellany, including possible catastrophic loss: All crops, conventional field crops or unconventional crops like algae, are subject to losses. These can come from the abiological environment, in the form of high or low temperatures. Controlling high or low T in an algal farm is likely to be quite expensive (fuel or electricity for heating; water for evaporative cooling). The threats can also come from biological sources. In the ocean, most algae and other plankton die in a fraction of a day to several days, primarily from viral infections and the like. In a contained culture, this threat might be reduced. However, a realized threat would spread with considerable speed, and decontamination is difficult and costly. With ordinary crops, soil microorganisms help control pathogens, if not completely. In algal farms, there is no such help. The risk is probably not insuperable, but it cannot be costed out currently for large operations.

Overall judgment: I can't see how algal farming, for biodiesel or power-plant fuel as biomass, is going to be an efficient use of land, water, and other inputs, or how it can even be a net energy provider, with anything like envisioned technologies. Why are people considering algal biodiesel and the like? I believe that there are many layers of wishful thinking or a failure to do the proper scaling-up arguments and life-cycle costing. As it has been put, just because something can be done is no reason to say it should be done. Another way to state it is by analogy: said of a dancing bear, it's not wonderful that it's done well, just that it's done at all.

There are many other alternative energy technologies that are far superior in both theory and practice. Among these are solar thermal, solar photovoltaic, and wind energy. Solar thermal has been practiced for over 15 years at the La Luz and other power plants in California, as an adjunct to natural-gas fueling at these plants. Both the solar technologies are poised to become very big players. New Mexico would do very well to invest in the technologies and in the jobs they bring. Wind energy is already a significant player in New Mexico, and more so in Texas. It is only 50% above market parity with coal-fired power plants and improving.

Future work: I'm pleased to provide this overview. If you or the state wants any extensive research, I'd be pleased to do it through my consulting group, the Global Change Consulting Consortium, Inc. Our Website is http://gcconsortium.com. We're a start-up, while we have already done a project for BP (formerly British Petroleum) for their operations in Azerbaijan. We are also in the midst of a contract with a 13-member research group addressing how best to use irrigation water and nitrogen fertilizer on valuable nut crops in TX, NM, and CA.