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The Need for a Biotechnology Revolution Focused on Energy and Climate Change

JJ Dooley

June 2001

Pacific Northwest
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ABSTRACT: Energy from purpose-grown biomass crops is an essential element in meeting future global energy needs and addressing climate change. "Business as usual" scenarios of the future already assume that large quantities of biomass--about 300 million acres--will be used for energy. When climate change mitigation is added to the modeled projections, the amount of biomass acreage increases to about 2,000 million acres. A change of this magnitude constitutes a transformation of the present energy system and significant changes in agriculture. Assessing the feasibility of this large a change in agricultural and energy systems requires (1) increased funding for energy from purpose-grown biomass crops; (2) integration of basic research, applied technology, social, and infrastructure considerations; (3) provision for ethical considerations, particularly of genetically modified crops that will be needed to allow biomass to be grown; (4) support for transition products and market conditioning; (5) research leading to high-yield plants that also enhance soil carbon sequestration; (6) monitoring systems to track carbon in plants and soils; (7) minimization of the costs of biomass energy; and (8) plant design for multiple objectives.

KEY WORDS: Bioenegy, biotechnology, energy, climate change, research and development.

Contents

This brief white paper reflects broad observations and insights relating to the role that biomass-derived energy can play over the next century. The insights are derived from the Integrated Assessment modeling (i.e., coupled energy/economic/impacts modeling) research carried out at Pacific Northwest National Laboratory (PNNL).[1] This paper is not intended to be a thorough analysis of this subject. Rather, the hope is to spark a discussion that would lead to a much more detailed analysis of the possible role for biomass energy and biotechnology and the science needed to make these nascent energy technologies a reality.

Not All Biomass Is Created Equal

Human uses of biomass-based energy sources can be grouped into three major historical paradigms, each of which rests upon a different technological foundation and uses a different set of key technologies to turn plant matter into useful forms of energy.

- *First Generation Biomass.* This could also be called traditional biomass. First generation biomass is typified by cutting down standing biomass (most likely trees) and directly burning it for its energy content either as wood or as charcoal. As can be seen from Figure 1, as recently as the late 1800s to early 1900s, this form of biomass energy accounted for more than half of the world's total primary energy supply. This form of biomass clearly has significant drawbacks associated with its continued use (e.g., deforestation). Therefore, it is extremely unlikely that first generation biomass can make significant contributions to meeting the world's growing demand for energy.
- *Second Generation Biomass.* This form of energy from plant matter is what currently characterizes the way many currently think about "biomass energy." It is typified by using food crops (e.g., using corn for ethanol) or by using at-hand biomass waste (e.g., using wood chips and bark to help generate process heat at a paper mill). This is clearly a step forward in our use of biological media for energy purposes, but it must also be seen as a fundamentally limited energy supply.
- *Third Generation Biomass.* Third generation biomass can best be described as crops that are specifically grown as an energy crop. Switchgrass (*panicum virgatum* L.) and poplar trees (*populus deltoides* L.) represent well-studied examples of third generation biomass.[2] At a global level, the contribution of "third generation biomass" is negligible today. As will be described below, the future of these biomass crops appears to be heavily intertwined with largely yet-to-be-developed bioengineering technologies, and new generations of process and

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[1] J.A. Edmonds, H.M. Pitcher, D. Barns, R. Baron, and M.A. Wise, "Modeling Future Greenhouse Gas Emissions: the Second Generation Model Description," in *Modeling Global Change* (Tokyo: United National University Press, 1995); J.A. Edmonds, M. Wise, H. Pitcher, R. Richels, T. Wigley, and C. MacCracken, "An Integrated Assessment of Climate Change and the Accelerated Introduction of Advanced Energy Technologies: An Application of MiniCAM 1.0, *Mitigation and Adaptation Strategies for Global Change* 1996, no. 4: 311-339.

[2] For example, Brown, R.A., N.J. Rosenberg, C.J. Hays, W.E. Easterling and L.O. Mearns. 2000. Potential production and environmental effects of switchgrass and traditional crops under current and greenhouse-altered climate in the central United States: a simulation study. Agric. Ecosystems Environment 78:31-47.

conversion technologies. Furthermore, the widespread use of third generation biomass will likely hinge on our ability to find socially acceptable ways to develop and deploy genetically modified organisms for food, fiber and energy crops.[3]

Most Business As Usual Projections of Future Energy Use Already Assume Heroic Penetrations of Biomass Energy

Most projections of future energy use and its impact on climate make use of "business as usual" scenarios like the Intergovernmental Panel on Climate Change's (IPCC) IS92a case, which is a mid-growth economic and demographic scenario that describes energy use over the course of this century.[4] However, it is perhaps much more accurate to describe the IS92a case as "innovation as usual" as opposed to "business as usual," as it contains a significant continued technological advancement (i.e., there is significant technological improvement *even in the absence of a climate management mandate*.)[5] For example, biomass energy crops and food crops (both of which compete for land) are projected to increase their productivity by 0.5% per year throughout this century simply as a matter of course (i.e., there are no explicit policies driving this sustained productivity increase). Figure 2 shows the large difference between continuing to use today's energy technologies and the "innovation as usual" IS92a projections.

Globally in the IS92a base case, people will consume about 30 exajoules of biomass energy every year by 2035. (See Figure 3 for an IS92a base case showing the degree of biomass energy production we are likely to require.) Again, this is 30 exajoules of biomass being required in the base case, i.e., this is *before* requirements such as carbon taxes are put in place to constrain emissions of greenhouse gases. What would 30 exajoules of biomass energy look like? Growing this amount of biomass would require 300 million acres be devoted to growing energy crops—approximately equal to 10 times the cropland contained in Iowa!

By the end of the century if we are on a pathway that would lead to atmospheric stabilization at 550 ppmv as described by Wigley, Richels and Edmonds (WRE)[6], biomass energy crops would consume more than 2,000 million acres globally by the year 2100. By the end of the current century, biomass energy crops would most likely be the largest single crop grown on this planet.

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[3] This is a key point. Crop productivities have increased substantially over the past half-century and that much of this is attributable to advances in conventional plant breeding and the continued adoption of better agricultural practices throughout the world. Equally, we can expect still more advances from continuing on these more conventional routes to improving agricultural efficiency. Less obviously but very importantly, most of these improvements in conventional practices are already assumed in the "base case." That is, we have already banked these gains and we still find ourselves needing to go much farther.

[4] Intergovernmental Panel on Climate Change (IPCC). (1992). Climate change 1992: The supplemental report to the IPCC scientific assessment. Cambridge: Cambridge University Press.

[5] The IS92a base case, for example, also assumes that energy end-use efficiency improves 1% per year every year throughout the course of this century. Fossil fired coal-based combustion is globally 44% efficient (up from the roughly 30% efficiencies of today).

[6] T.M.L. Wigley, R. Richels, and J.A. Edmonds, "Economic and Environmental Choices in the Stabilization of Atmospheric CO_2 Concentrations," *Nature* 1996, 379(6562): 240-243.

Economic modeling carried out at PNNL suggests that the ability to field biomass as a significant contributor to the world's energy supply in a WRE550 stabilization scenario could result in reducing the cost of atmospheric stabilization by as much as $540 billion dollars over the course of this century.[7]

Its important to take a step back and ask if creating this amount of energy via biomass is plausible without moving to a fundamentally different technological basis.

Biomass Energy Use Might Even Be Higher

Modeling carried out at PNNL suggests that a significant fraction of the early emissions reductions needed to get the world onto a path that would lead to stabilizing atmospheric concentrations of CO_2 at 550 ppmv would come from technologies that we are only beginning to research and that remain significantly far from ready for large scale commercial deployment.

For example, by 2035, perhaps as much as 60% of the global emissions reductions needed to achieve a 550 WRE stabilization trajectory would come from the massive deployment of soil carbon sequestration practices, engineered carbon capture and sequestration in geologic reservoirs and third generation biomass. We estimate that present investments in these three types of technologies are token at best, perhaps accounting for no more than 5% of global public and private sector energy R&D investments.[8] Given that 30–40 years are typically required for energy technologies to go from the research stage to full scale commercial deployment, we should evaluate whether the current amount of R&D will yield large scale global deployment of these technologies.

If we cannot rely on a technology such as engineered carbon sequestration to the extent that we currently expect,[9] then some other technology will have to deploy even more aggressively to take up the slack. Given that all energy technologies have some inherent constraints on their deployment (e.g., societal concerns about nuclear power, the need to connect solar systems to costly storage technologies if we wish to rely on them for a significant fraction of base load power), it is not unreasonable to assume that we would need to rely on biomass (a fairly acceptable energy technology) to an even greater extent that the figures above indicate.

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[7] In fact, the savings are likely significantly more than this as this was an intentionally conservative calculation.

[8] J.J. Dooley and P.J. Runci, "Developing Nations, Energy R&D, and the Provision of a Planetary Public Good: A Long-Term Strategy for Addressing Climate Change," *The Journal of Environment and Development* 9 (September 2000): 216-240.

[9] Engineered carbon capture and sequestration could result in as much as 2-4 Gt of carbon (C) being stored in geologic reservoirs annually by 2050. That is a truly staggering amount of C that would need to be sequestered given that we have relatively little idea where these reservoirs lie around the world, relatively little idea of their total absorptive capacity, and practically no idea how long the injected CO2 would remain in these formations.

Thoughts About R&D for Third Generation Biomass

1. ***Research Support Needed:*** The US government already spends a considerable sum on bioenergy R&D (perhaps in excess of $240 million in FY2000 at the US Department of Energy [USDOE] and the US Department of Agriculture [USDA]), yet a truly minor fraction of this investment appears focused on what is being referred here to as third generation biomass. Even with generous assumptions about focus of these R&D programs, less than 13% of the US government's investments in bioenergy appear to be targeted at the types of biomass crops and technologies that will be needed simply to power the global economy in the coming decades—let alone make a significant contribution to addressing climate change. That is, relatively little R&D is spent on third generation biomass. The vast majority of the US bioenergy R&D program (of FY2000) appears to be focused on "second generation biomass" and in particular R&D designed to use food crops and crop residues as a feedstock for transportation fuels.[10] This would then suggest that an important first step would be to look at the current federal bioenergy portfolio and ask if it is focused on R&D that will be needed to bring about the large-scale deployment of third generation biomass. A second order task would be to begin building a case for a significantly larger R&D effort in third generation biomass.
2. ***R&D Integration:*** Large-scale deployment of bioenergy will require a fundamental transformation of a large segment of the US energy system. This transformation will fail unless the R&D effort fully integrates basic science, applied technology, social, and infrastructure considerations. Stovepiped scientific basic research in one part of the Federal sector will not magically "connect" with stovepiped applied research in other parts of the Federal sector. There must be an integrated approach to both ensure the combined scope of all R&D is focused on the right targets, that basic science ultimately has an applied outlet, and applied programs are able to "dive into" the underlying science when roadblocks are encountered.
3. ***Ethical Considerations:*** We will probably not be able to produce this much biomass-based energy and enough food for a growing world population absent a significant reliance on genetically modified organisms for bioenergy production and perhaps for food as well.[11] Given that the use of these crops remains a contentious issue, it might be wise to form a program similar to the Human Genome Program's Ethical Legal and Social Issues (ELSI) as an integral part of any major bioenergy R&D program. Ethical and social issues, if not addressed proactively, could easily derail the introduction of these technologies.

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[10] To be fair, the US government R&D program on bioenergy or any other technology must struggle to find an appropriate balance between near-term and long-term R&D needs of the country. The focus of this paper is solely on the long term and therefore the tone of the comments here might seem unnecessarily harsh. Also the binning of these R&D programs into "second generation" and "third generation" was not done at the project level, but rather was based upon high level program descriptions found in budget documents.

[11] This is a critical point. Since bioenergy crops and food and fiber crops will (largely) compete for the same land there must be sustained productivity growth for food, fiber and energy crops or else the competition for land will significantly drive up the prices of all crops.

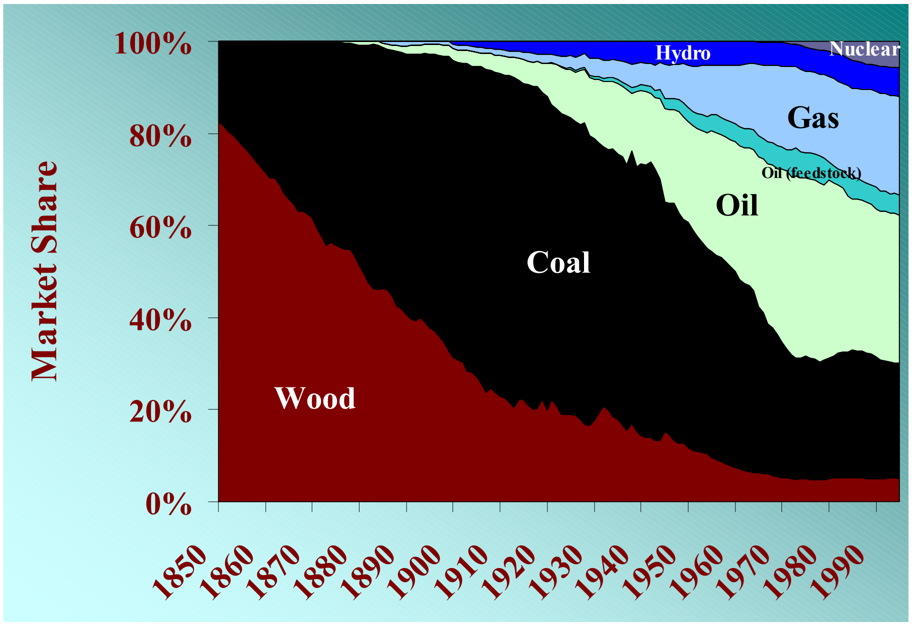
4. ***Transition Products and Market Conditioning:*** Biofuels and bioelectricity are the two energy forms that have significant leverage on reducing CO_2 emissions. Biochemicals or other bioproducts do not mitigate significantly large amounts of CO_2 to profoundly address climate change; however, many of these products are higher value products that will be early entrants to the marketplace, conditioning it for the broader entry of biofuels and bioelectricity into the marketplace. Therefore, we should selectively pursue R&D that enables the development and early entry of high value bioproducts into the market. These products will undoubtedly rely on many of the same biological understanding and process engineering understanding that will later benefit the development of fuels and electricity. Yet it is important to realize that for bioenergy to deliver significant reductions in global CO_2 emissions over this century, the overarching goal must be to make bulk and relatively inexpensive energy commodities via biotechnology.
5. ***Dual Benefits:*** Not only are we likely to rely on agricultural lands for biomass energy production, but we are also likely to place heavy demands on these same lands in terms of using them for soil carbon sequestration. By the end of this century, PNNL modeling suggests that all agricultural lands will have switched over to soil carbon sequestration practices. Therefore, it will be important to consider the interplay between these (perhaps competing or perhaps synergistic) uses for agricultural lands and to begin to develop technologies that will allow us to maximize the benefit to be had by simultaneously using the same land to grow advanced biomass energy crops and to sequester carbon in the soils. For example, one could imagine plants that uptake large amounts of CO_2 during their lifetime, sequestering it in their root system, while simultaneously growing foliage that is highly amenable to extraction of natural sugars that would later be used for energy production.
6. ***Monitoring:*** Given the dual use of land as a sequestration sink and resource for growing biomass, linked by the overarching objective of reducing atmospheric carbon, advanced carbon monitoring systems will be a critical component of the bioenergy system of the future. Such monitoring systems are likely combinations of terrestrial, remote, and/or satellite based.
7. ***Economic Considerations:*** Attractive economics are critical to successful deployment of bioenergy. Biofuels and bioelectricity will be inherently low-value, high-volume products in the global economy. Therefore, biomass production, transportation, and processing costs must be cut dramatically from current costs of today's biofuels. This almost certainly will drive us towards one of two biomass production approaches: (1) decentralized or possibly in-field processing of biomass to ensure that the minimum mass and highest-value product is transported, or (2) biomass that is harvested at a point in its life-cycle when no water remains in the plant and its content is extraordinarily high in the right kinds of molecules (e.g., natural sugars).
8. ***Plant Design for Multiple Objectives:*** To deploy biomass energy crops on a large scale will require substantially more than tinkering with one gene at a time in a crop; we must understand them at a "systems" level. Plants have evolved many different features, such as predator defenses, that are required for survival in the

wild, but are dispensable for high-yield biomass crops. Plants have also evolved mechanisms that allow them to tolerate different climatic extremes, but many of these features could substantially reduce biomass yield. Theoretically, one should be able to design a modular biomass crop plant in which groups of genes could be added or subtracted to produce specialized plants that are optimized for a given set of local climatic or soil conditions. This would produce the greatest amount of biomass for a given location. Understanding how to create modular crops would greatly enhance our ability to design biomass feedstocks that meet multiple objectives, including (1) extraordinarily high crop yields compared to today's crops; (2) sequestration of CO_2 below ground while producing valuable crop mass above ground; (3) crops that are disease resistant and drought tolerant to minimize the need for pesticides, herbicides, and water; (4) crops that are extremely amenable to subsequent chemical or biological processing to fuels or electricity; and (5) crops that, if requiring centralized processing, are extraordinarily lightweight.

Conclusion

Using purpose-grown biomass as a low-emissions energy source is a potentially low cost method to address climate change risks. However, the scale of such an undertaking is enormous, constituting a transformation of global energy system. Large-scale biomass energy requires substantial advances in the basic science of plant design, an integrated approach to basic and applied research, concurrent consideration of ethical and economic issues, effective planning for market transition, and reliable monitoring systems. Biomass energy is a straightforward concept but a complex endeavor necessitating a coordinated, programmatic effort.

Figure 1: Global Market Shares of Various Energy Sources[12]



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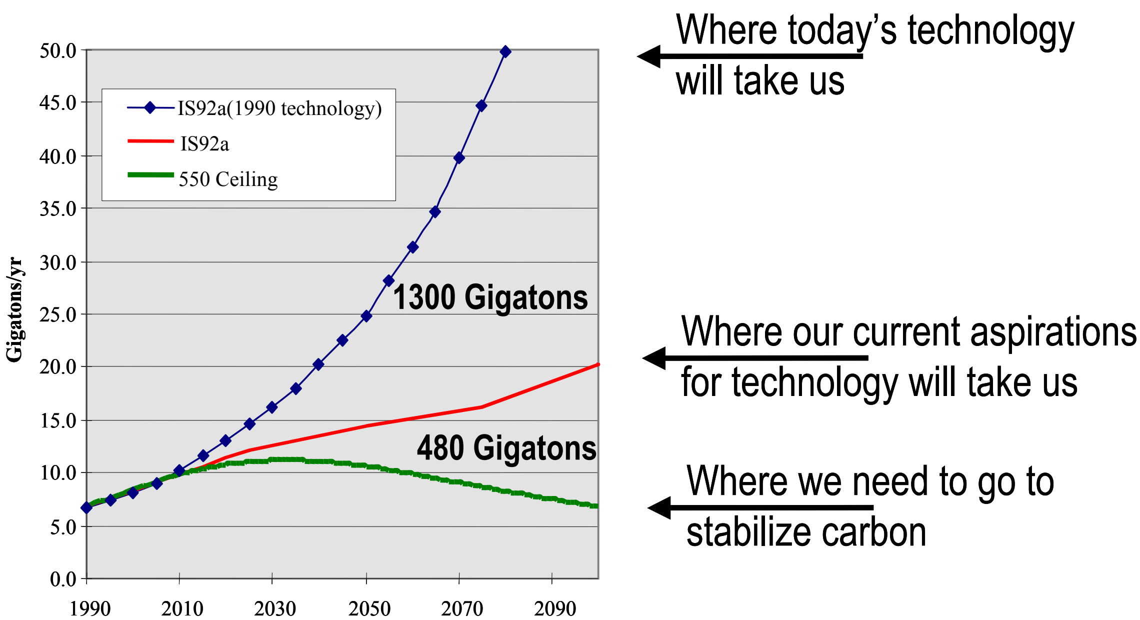
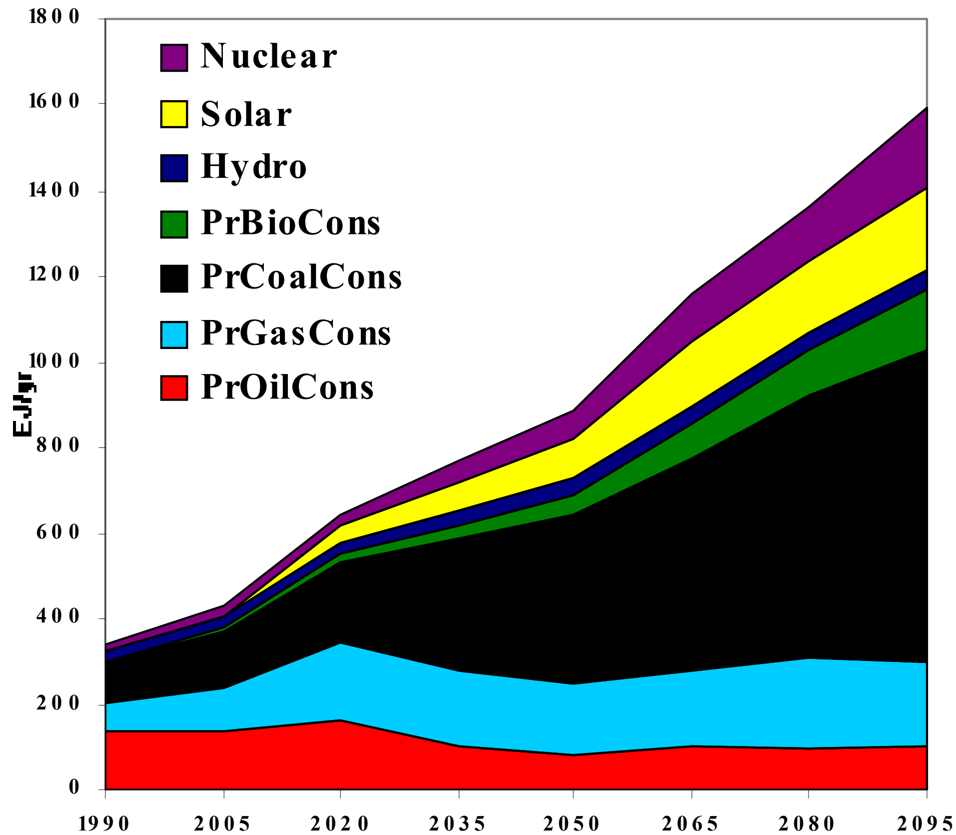
[12] Source: N. Nakicenovic, personal communication, 2000.

Figure 2: Global Emissions of CO_2 Over This Century for
Three Technology Scenarios: Frozen 1990 Technology, IS92a, and the
Technological Performance Embedded in a WRE550 Stabilization Scenario



Note: The area between the Froze 1990 technology curve and IS92a is equivalent to 1300 Gt of crbon. That is the technological innovation assumed within the IS92a curve is expected to avoid 1300 Gt of carbon from being released into the atmosphere with respect to the case in which the world continued to use 1990 state-of-the-art technologies. This however still leaves the world 480 Gt of carbon "over budget" if we are to stabilize atmospheric concentrations of greenhouse gases at 550 ppmv. This then strongly implies that we must go significantly beyond the technological improvements already assumed within IS92a.

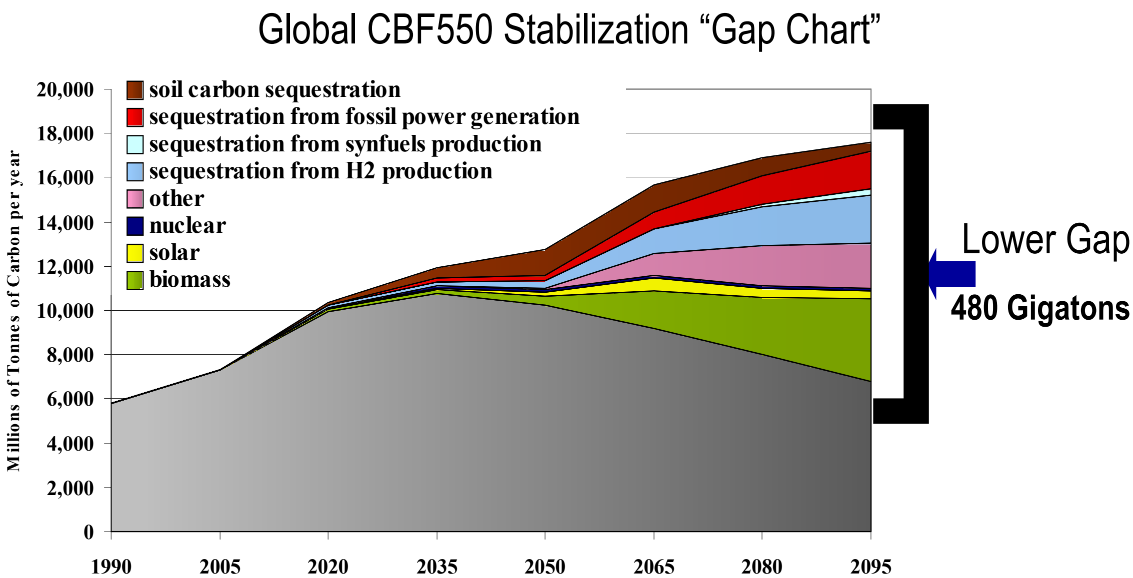
Figure 3: Reference (i.e., IS92a) Global Energy Consumption by Fuel-Type Over the Coming Century Assuming Continued Abundant Coal Supplies and Limited Inexpensive Oil and Gas Resources[13]



Note: "PrBioCons" stands for primary energy consumed from biomass energy. Likewise, PrCoalCons stands for primary energy consumed from coal and coal-based products. PrGasCons stands for primary energy consumed from natural gas. PrOilCons stands for primary energy consumed from oil.

[13] This is the Pacific Northwest National Laboratory MiniCAM "Coal Bridge to the Future (CBF)" scenario. For a full explanation of this scenario, see J.A. Edmonds and M. Wise, "Building Backstop Technologies and Policies to Implement the Framework Convention on Climate Change," *Energy & Environment Special Issue—Climate Change Policy in Western Europe and the USA* 1998, no. 4: 383-97.

Figure 4: Emission Reduction Contribution by Technology in a CBF[14] World Needed to Close the Gap Between IS92a and a WRE 550 Stabilization Scenario



[14] This is the Pacific Northwest National Laboratory MiniCAM "Coal Bridge to the Future (CBF)" scenario. See Edmonds and Wise, op cit.