RESEARCH BRIEF: GRASS PELLETS

ABSTRACT

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This brief examines the feasibility and environmental impact of using grass pellets as a heat and energy source. Grass production and combustion generates significantly less carbon dioxide than fossil fuel production and combustion; in addition, cultivating grass would also remove significant amounts of carbon dioxide from the atmosphere as the grass root systems would sequester carbon in the ground. Grass cultivation would also have beneficial effects for rural area economies and for the soil.

The cultivation, harvesting and pelletization of bioenergy grasses has been repeatedly demonstrated. Although there are currently no stoves specifically designed for use with grass pellets, other stoves have been successfully adapted. The current lack of a grass pellet market means that price estimates for grass pellets are subject to a degree of uncertainty. In the short-run, grass pellets are probably not price competitive with fossil fuels for home electricity generation (although there is strong future potential if the government requires carbon permits and trading). For home heating, it is reasonable to believe that grass pellets are comparable in price to (or potentially slightly cheaper than) low-cost sources such as corn, wood, wood pellets, and natural gas.

ARGOSY FOUNDATION

Rural Impact

Rural Economies

- The New England Grass Pellet Collaborative (NEGPC) report emphasizes, correctly, the potential economic benefits for rural areas from grass cultivation and pellet production
- In 2000, the median family income in metropolitan areas was $55,203 while it was $41,829 in non-metropolitan areas[1]
- For the past ten years, the poverty rate has been roughly two percentage points higher in non-metropolitan areas compared to metropolitan areas[2]
- Widespread cultivation of energy grasses would reduce the supply of annual crops, potentially leading to increases in annual crop prices (and increases in rural incomes), reductions in government farm subsidies, as well as substantial profits to farmers raising energy crops[3]
- The energy market is a huge potential market: roughly $689 billion was spent on energy in the United States in 2000, equal to about 7 percent of GDP[4]

Environmental Impact[5]

Carbon Emissions

- Combustion of fossil fuels releases carbon dioxide, which is, of course, a "greenhouse" gas[6]
- While combustion of grass also releases carbon dioxide, the carbon dioxide was recently absorbed from the atmosphere through photosynthesis, in contrast to fossil fuels where the carbon was absorbed tens of millions of years ago; this means that grass combustion adds much less carbon to the atmosphere than fossil

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[1] U.S. Department of Agriculture, Economic Research Service.
[2] U.S. Department of Agriculture, Economic Research Service.
[3] One study estimates roughly $5 billion in annual farmer profits by 2025. N. Greene "Growing Energy: How Biofuels Can Help End America's Oil Dependence." National Resources Defense Council. 2004.
[4] The vast majority of this energy (roughly 86 percent of output) was produced using fossil fuels, and less than 3 percent was produced using biofuels. U.S. Department of Energy, Energy Information Administration (http://www.eia.doe.gov/emeu/aer/overview.html).
[5] Some articles list metric units of measurements and some list English units. In this paper I will consistently use kilograms, short tons (2000 lbs), and acres because I think those units of measurement are likely to be familiar. For heat, I will typically use British Thermal Units. One BTU is roughly the amount of heat need to raise one pound of water by one degree Fahrenheit.
[6] Although there is some debate in the political arena about humanity's role in global warming, there is a relative scientific consensus that our production of carbon dioxide is contributing to global warming. According to the National Academy of Sciences: "Greenhouse gases are accumulating in Earth's atmosphere as a result of human activities, causing surface air temperatures and subsurface ocean temperatures to rise. Temperatures are, in fact, rising. The changes observed over the last several decades are likely mostly due to human activities, but we cannot rule out that some significant part of these changes is also a reflection of natural variability." National Academy of Sciences Committee on the Science of Climate Change. "Climate Change Science: An Analysis of Some Key Questions." 2001.

fuel combustion

- However, cultivating, harvesting, and pelleting grass does use energy (most likely fossil fuels) and thus the net reduction in carbon emissions depends, in part, on how much fossil fuel is used in the life-cycle production of the grass pellets
    - Three studies have examined the amount of energy used in the production of grass up to, but not including, the pelleting process, and all three of the studies estimate that comparatively little amounts of fossil fuels are used in the cultivation and harvesting of energy grasses[7]
    - The entire lifecycle grass pellet process (including pelleting[8]) is estimated to have an energy output to input ratio of 14.6:1[9]
- During the entire lifecycle (i.e. from production through combustion), it is estimated that using heating oil will produce 89.7 kg carbon dioxide/gigajoule, natural gas will produce 62.1 kg of carbon dioxide/gigajoule, propane will produce 71.1 kg of carbon dioxide/gigajoule, wood pellets will produce 8.2 kg of carbon dioxide/gigajoule, and grass pellets will produce 8.2 kg of carbon dioxide/gigajoule[10]; another study estimates that grass combustion will produce 163 fewer kilograms of carbon dioxide per million BTUs than coal combustion which is often used to generate electricity[11]

Other Greenhouse Gas Emissions

- In addition to carbon, other gases like nitrous oxide and methane also trap heat in the atmosphere and thus contribute to global warming
- On a weight basis, nitrous oxide is a much more powerful greenhouse gas than carbon dioxide; the greenhouse effect of nitrous oxide is 310 times greater than carbon dioxide
- Nitrogen is often used a fertilizer for crops; because energy grasses need less nitrogen fertilizer than conventional crops, replacing annual crops with energy

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[7] The first paper estimates that the ratio of carbon contained in the harvested grass to carbon used in production was roughly 41:1 for SG and 30:1 for RCG. M. Bullard and P. Metcalfe. “Estimating the Energy Requirements and CO_2 Emissions from Production of the Perennial Grasses: Miscanthus, Switchgrass, and Reed Canary Grass.” 2001. The second paper estimates that for each unit of fossil fuel energy used to produce SG, 11 units are returned in energy. David Pimental and Tad Patzek. “Ethanol Production Using Corn, Switchgrass, and Wood; Biodiesel Production Using Soybeans and Sunflower.” *Natural Resources Research*. 2005. The final paper estimates that the fossil fuel input to energy output ratio for SG production to be 23:1. Roger Samson, Patrick Duxbury, and Lindsey Mulkins. “Research and Development of Fibre Crops in Cool Season Region of Canada.” 2004.

[8] Pelleting achieves a dense fuel that makes it easier to control the combustion process, obtain a high heat recovery and ensure clean combustion.

[9] Roger Samson, Patrick Duxbury, and Lindsey Mulkins. “Research and Development of Fibre Crops in Cool Season Region of Canada.” 2004.

[10] R. Jannasch, R. Samson, A. de Maio, T. Adams, and C. Ho Lem. “Changing the Energy Climate: Clean and Green Heat from Grass Biofuel Pellets.” 2001.

[11] The SG in this study was not pelletized but was used in bales; pelletizing would increase the carbon emission. Richard Ney and Jerald Schnoor. “Greenhouse Gas Emission Impacts of Substituting Switchgrass for Coal in Electric Generation: The Chariton Valley Biomass Project.” Schnoor Center for Global and Regional Environmental Research. 2002.

grasses would be expected to reduce nitrous oxide emission by 0.12 kg of nitrous oxide/acre a year[12]

Carbon Sequestration

- Grasses remove carbon dioxide from the atmosphere during photosynthesis and part of the carbon is then converted into grass roots; perennial grasses have extensive and deep root systems and harvesting the grass leaves the roots, including the carbon component, underground, meaning that the carbon will not combine with oxygen to form carbon dioxide in the atmosphere[13]
- While energy grasses' roots add carbon to the soil, clearly this addition does not occur indefinitely, and one study estimates that the maximum amount of carbon is added after seven years and there is carbon stability after that point[14]
- One study estimates that perennial grass roots can add over 400 kg of carbon per acre to the soil on an annual basis, while another study estimates that switchgrass (SG) stores 288 kg of carbon per acre annually for the first ten years, with declining sequestrations after that point[15]
- If energy grasses permanently replace perennial crops they could be expected to remove 73.2 carbon dioxide tons/acre and 76.2 carbon dioxide tons/acre over time, although if the grasses replaced other grasses, there would be little new carbon sequestration[16]
- In peat soils (i.e. non mineral soils), grass cultivation can also significantly reduce the carbon oxidation (forming carbon dioxide) that occurs with annual crop cultivation, reducing carbon emissions by roughly three tons/acre annually[17]

Reed Canary Grass (RCG) Can Reduce Ecological Diversity

- Once established, RCG is difficult to eradicate due to its extensive root system
- RCG is currently considered a "pest species" in nine states, including Vermont

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[12] Pal Borjesson. "Environmental Effects of Energy Crop Cultivation in Sweden—1: Identification and quantification." *Biomass and Bioenergy*. 1999.

[13] Grasses add less carbon to the soil in cooler climates.

[14] As the roots decay over time they release carbon dioxide, and this carbon dioxide roughly balances the new carbon continuously added through the root systems. M. Bullard and P. Metcalfe. "Estimating the Energy Requirements and CO_2 Emissions from Production of the Perennial Grasses: Miscanthus, Switchgrass, and Reed Canary Grass." 2001, p. 55.

[15] S. McLaughlin, D. Ugate, C. Garten, L. Lynd, M. Sanderson, V. Tolbert, and D. Wolf. "High-Value Renewable Energy from Prairie Grasses." *Environmental Science and Technology*. 2002. p. 2124. Another study finds that SG adds little carbon to the soil during the first three years of cultivation, but by the tenth year SG cultivation increased soil carbon by roughly 45 percent compared to fallow soil. Z. Ma, C.W. Wood, and D.I. Bransby. "Soil management impacts on soil carbon sequestration by switchgrass." *Biomass and Bioenergy*. 2000.

[16] "Estimating the Energy Requirements and CO_2 Emissions from Production of the Perennial Grasses: Miscanthus, Switchgrass, and Reed Canary Grass." 2001, pp. 57-8.

[17] Pal Borjesson. "Environmental Effects of Energy Crop Cultivation in Sweden—1: Identification and quantification." *Biomass and Bioenergy*. 1999.

[17] Pal Borjesson. "Environmental Effects of Energy Crop Cultivation in Sweden—1: Identification and quantification." *Biomass and Bioenergy*. 1999.

- Some strains of RCG are not invasive; however, there has been a continuous hybridization problem between non-invasive strains and invasive strains in Vermont and the hybrids have tended to grow very fast and dominate landscapes[18]
- Certain practices could theoretically reduce the danger posed by invasive RCG (e.g. harvesting before seed formation)[19], but there are often corresponding drawbacks (early harvesting would cause high ash concentrations in the RCG)
- Joy Zedler, a Professor of Botany at the University of Wisconsin-Madison, told me "the short answer is that I think that planting new stands of this invasive plant [RCG] is a terrible idea"[20]; she was much more positive about SG
- Prof. Zedler was skeptical of harvesting practices that could minimize the possibility of invasive RCG, but did acknowledge that under limited circumstances, RCG might be relatively innocuous
- A British study examined how RCG and SG cultivation affected plant, animal and insect biodiversity; the study concluded: "These results clearly demonstrate that perennial biomasss grasses grown as an energy source have a positive effect on biodiversity and can benefit native wildlife."[21]; it is important to note that this study occurred in the United Kingdom where RCG is not considered invasive (there is some debate about whether RCG is indigenous to North America or was instead brought over by early settlers)
- Converting fields planted with crops to SG increases the number of some bird species while reducing the number of other bird species;[22] to the extent that SG and RCG cultivation reduce the use of pesticides and annual plowing (compared to annual crops), they would be expected to have positive effects on environmental diversity

Grass and Soil

- The grasses' deep root system (roots can extend 2.7 to 3.6 meters) can significantly prevent erosion[23] (2.34 percent of Colorado land and 0.77 percent of Vermont land is severely eroded); for example, while soil erosion for land

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[18] Communication with Jane Molofsky, Associate Professor of Botany at the University of Vermont.
[19] Communication with Jane Molofsky, Associate Professor of Botany at the University of Vermont.
[20] Both Professors Molofsky and Zedler would be interested in providing further information if needed. There is a working group on RCG in Madison and I was invited to attend some of their meetings.
[21] This attempt at SG cultivation was relatively unsuccessful in the UK (others have succeeded) and these results are for RCG. Tzehaye Semere and Fred Slater. "The Effects of Energy Grass Plantations on Biodiversity." 2005.
[22] Les Murray, Louis Best, Tyler Jacobsen, and Martin Braster. "Potential Effects on Grassland Birds of Converting Marginal Cropland to Switchgrass Biomass Production." *Biomass and Bioenergy*. 2003.
[23] The erosion reduction might be a factor of 100 when compared to common cash crops. J. King. "Reducing Bioenergy Costs by Monetizing Environmental Benefits of Reservoir Water Quality Improvements from Switchgrass Production: Pelletized Switchgrass for Space and Water Heating." 1999.

cultivated with SG and RCG was less than half a ton/acre, land cultivated with corn had soil erosion of between 2-15 tons/acre[24]

- The grasses' root system adds organic matter (soil organic carbon) to the soil and the cover helps prevent nitrate (a nutrient) leaching
- SG rejuvenates soil: a study comparing crop yields found that crops planted on land that had previously grown SG yielded 87 percent more corn, 37 percent more soybeans, and 27 percent more cotton than control plantings[25]
- Locating SG and RCG fields between annual crops and open streams could reduce water pollution from fertilizer runoff and other nutrient leaching[26]

Feasibility

Grass Production Logistics

- Grass would typically be grown on less fertile land; growing grass on productive cropland (and displacing crops) would be less cost competitive
- Grass can be cut and baled with conventional mowers and balers
- SG and RCG are perennials; once established (may take two years) they can be harvested annual for roughly ten years before replanting is needed
- Grass is relatively sustainable: repeated harvesting of SG do not affect the future productivity of the grass, at least over a 15 year period[27]
- To minimize transportation costs, which can be expensive, it would be efficient to have the pelleting process occur near both grass producers and pellet consumers

Grass and Ethanol

- SG can be used to make ethanol (microbes are used to convert the SG raw material to ethanol and energy is then used to refine the ethanol)
- Converting SG to ethanol uses fossil fuels, but the U.S. Energy Department estimates that the ethanol returns more energy than is used in ethanol production[28]

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[24] A. Hallam, I.C. Anderson, and D.R. Buxton. "Comparative Economic Analysis of Perennial, Annual, and Intercrops for Biomass Production." *Biomass and Bioenergy*. 2001.

[25] The control crops were planted on land that had been colonized by natural grasses and plants. T. Morrison, D. Bransby, S. Sladden, and V. Tolbert. "Soil Improvements Related to Switchgrass as Indicated by Subsequent Crop Yield." Another study estimated more modest improvements of roughly 5 percent. Pal Borjesson. "Environmental Effects of Energy Crop Cultivation in Sweden—1: Identification and quantification." *Biomass and Bioenergy*. 1999.

[26] Pal Borjesson. "Environmental Effects of Energy Crop Cultivation in Sweden—1: Identification and quantification." *Biomass and Bioenergy*. 1999.

[27] C.W. Rice, G.W. Wilson, J. Blair, and P. White. "Soil Quality as Affected by Biomass Removal in Tallgrass Prairie." *American Geophysical Union*. 2003.

[28] The Department's estimate is based on converting corn to ethanol. For more information see: http://www1.eere.energy.gov/biomass/net_energy_balance.html. There is some disagreement about the merits converting SG to ethanol. One study estimates that converting SG to ethanol uses about 50 percent more fossil energy than the ethanol returns in energy. David Pimental and Tad Patzek. "Ethanol Production Using Corn, Switchgrass, and Wood; Biodiesel Production Using Soybeans and Sunflower." *Natural Resources Research*. 2005. In contrast, another expert, Sandy McLaughlin estimated that SG ethanol outputs 4.3 times the amount of energy needed to

- A recent review finds that SG ethanol has strong potential as a biofuel because: SG can be grown on marginal land and does not displace food production, SG ethanol has the *potential* to return 300 percent more energy than is used to produce it, and SG production uses little fertilizer and pesticides[29]

Grass Pellets and Electricity

- Grass has been used to generate electricity: demonstrations have occurred both in industrial power plants[30] and microgenerators that can be located at houses
- The NEGPC report advocates using grass to generate electricity at homes and farms and the report discusses the BioMax system (has been tested with grass pellets) and the STM Power System (has not been tested with grass pellets)[31]
- The company that manufactures the BioMax states that it is a "good fit" for businesses that generate biowaste and it is a "bad fit" for "residential applications where power is obtained from the grid"
- The NEGPC report provides information that I used to estimate an operating cost of 15.3 cents a kWh for electricity plus 600,000 kWh of (free) thermal energy that can be used for heating;[32] this estimate does not include the equipment cost
- As this cost of grass pellet electricity is significantly higher than power off the grid, the economic competitiveness of grass pellet electricity depends on the value of the thermal energy generated as a byproduct; efficiently utilizing the heat is essential for cost competitiveness[33]
- Usually home generation systems are not cost-competitive due to the economies of scale in electricity generation;[34] however, by also utilizing the heat byproduct of electricity generation, combined home heat-power systems can be competitive
- REAP-Canada, often cited in NEGPC report, believes that grass-powered electricity generation is not "economically sustainable" at this point and recommends focusing on heat initially, and then heat-power systems[35]

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make ethanol. Another study also found beneficial energy ratios. S. McLaughlin, D. Ugate, C. Garten, L. Lynd, M. Sanderson, V. Tolbert, and D. Wolf. "High-Value Renewable Energy from Prairie Grasses." *Environmental Science and Technology*. 2002. p. 2124. Of the literature I read and people I talked to, most believe that SG ethanol returns more energy than is used to make it.

[29] The authors conclude that, assuming continued technological progress, SG ethanol is strongly preferable to corn ethanol. Jason Hill, Erik Nelson, Stephen Polasky, and Douglas Tiffany. 2006. *Proceedings of the National Academy of Science.*

[30] Wade Amos. "Results from Chariton Valley Biomass Project: Switchgrass Co-fire Testing."

[31] None of the references listed in the NEGPC report addressed the relative cost compared to electricity "off-the-grid."

[32] The NEGPC report estimates that a BioMax 50 would use 370 tons of grass pellets (in the next section I estimate the price of pellets at $134 a ton) and this will produce roughly 324,00kWh of electricity (p. 14).

[33] While the BioMax is only 25-30 percent efficient when generating only electricity, it is 70-80 percent efficient when generating electricity and heat.

[34] For example, while power plants can burn baled grass, home generation systems require the additional step of having the grass pelleted. Cornell Professor Jerry Cherney stated "No doubt whole bale systems are more economical and energy efficient" than pelleting systems, but he also believes that high transportation costs often make centrally located power plants uneconomical.

[35] Conversation with Roger Samson and http://www.reap-canada.com/bio_and_climate_3_2.htm

- However, a recent study found that co-firing SG with coal in industrial power plants is cost competitive (including the cost of future regulatory compliance and subsidies) and significantly reduces harmful emissions[36]
- If the government enacted a carbon permit and trading system, this would make grass-powered electricity generation very price competitive

Grass Pellet Stoves

- Currently no company is manufacturing stoves specifically designed to burn grass pellets, but some wood pellet and corn stoves have been successfully adapted and used to burn grass pellets[37]
- The stoves that have been demonstrated to burn grass pellets are somewhat higher in price (roughly $1000 or less) than high-efficiency natural gas furnaces, but increased stove production would be expected to reduce costs
- Using stoves involves more work than natural gas or oil furnaces; pellets must be loaded (although there are hoppers than can automatically release pellets for a few days) and ash must be cleaned out once or twice a week (some studies indicate the ash can be used to increase alkaline levels in the soil)

True Cost Estimates

- Market prices for energy often do not reflect the true social cost of the energy source because the production or usage of the energy often imposes costs on individuals not involved (in economics, this is called a negative externality)
- For example, using gasoline emits pollution (including carbon dioxide) and the vast majority of the costs will be paid by individuals other than the driver of the car and the oil company (e.g. coastal regions disappearing); one study estimates that the economic value of reducing carbon by one ton is between $54 and $327[38]
- Moreover, American reliance on oil and natural gas imposes an energy dependency on other countries, and there are clearly significant costs involved in protecting those energy sources
- If the price of fossil fuels included all their social costs, the price would clearly be much higher (although the amount of the appropriate price differential is disputed, the basic principle of negative externalities is endorsed by almost all economists)
- Thus price comparisons between bioenergy and fossil fuels, while important for measuring the likelihood that people will use the fuel, are not an accurate measure of the overall cost and benefits to society because bioenergy has significantly fewer negative externalities (this is the rationale behind carbon permits)

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[36] J. Solow, R. Ney, M. Balch, J. Schnoor, O. Sivan. "Estimating the Economic Impact of Substituting Switchgrass for Coal for Electricity Generation in Iowa." 2005.

[37] http://www.grassbioenergy.org/res/pellet_stove_demo.asp#cpc

[38] This estimate is based on the cost of reducing carbon emissions by one ton. The wide range occurs because it is much easier to reduce carbon in some circumstances than others (e.g. it is cheaper to replace coal than gasoline). Pal Borjesson. "Environmental Effects of Energy Crop Cultivation in Sweden—II: Economic Valuation." *Biomass and Bioenergy*. 1999.

Market Cost Estimates

- Market costs are essential for understanding to what degree people will use grass pellets without subsidies or other financial incentives
- In the Northeast (non-rural) the primary available heating sources are electricity and fuel oil, although natural gas is becoming more common; in the rest of the U.S. (non-rural) the primary sources are natural gas and electricity; in rural areas, the primary heating sources are propane and wood
- The NEGPC report (page 9) and my analysis below provides estimates of the cost of using grass pellets for heat; the estimates only detail the cost of the fuel, and a complete analysis would also consider the amortized cost of the stove, the cost of fuel storage for certain fuels, maintenance, and the cost (hassle) of restocking fuel and removing ash; many of these costs are likely to be higher for grass pellets
- The per unit cost for grass pellets does not include a profit for the farmer or pellet producer, while the cost for other fuels is the current market cost
- I estimated the fuel costs using independent sources (see footnotes), and my estimates were close to the estimates in the NEGPC report, although NEGPC estimates, except for propane and grass pellets, were usually higher than mine

Fuel Type	**Number of BTU/Unit**[39]	**Cost per unit**[40]	**Heat Efficiency**[41]	**Cost per million BTU**[42]
Fuel Oil (#2)	140,000/gallon	$2.40	80-89%	$20.20
Propane	91,330/gallon	$2.24	80%[43]	$30.60
Electricity	3,412/kWh	13 cents	97-99%	$38.80
Wood (air dried)	20,000,000/cord	$170	65-75%	$12.10
Wood Pellets[44]	16,500,000/ton	$210	85-90%	$14.50
Dry Shell Corn	392,000/bushel	$4.00[45]	80%[46]	$12.70
Natural Gas	1,025,000/1000 cf	$13.60	85-97%	$14.50
Grass Pellets (bulk)	16,200,000/ton[47]	$132[48]-149[49]	82%	$9.94-$11.22[50]

[39] U.S. Energy Department: www.eere.energy.gov/consumer/your_home/space_heating_cooling/index.cfm/mytopic=12330

[40] The Vermont Department of Public Service estimated the price in Vermont during December 2005 (http://publicservice.vermont.gov/pub/fuel-price-report/05dec.pdf)

[41] This efficiency rate assumes the person uses a high-efficiency furnace. To compute the cost per million BTU, I took the average of the efficiency rates.

[42] The Vermont Department of Public Service, estimates lower efficiency for the stoves, and thus estimates slightly higher cost per million BTU's; the DPS estimates are: fuel oil: $21.72, propane: $30.55, electricity: $37.51, wood: $12.88, wood pellets, $16.01, and natural gas: $17.00. Except for propane, these estimates are slightly lower than the estimates in the NEGPC report.

[43] This number is from the Vermont Department of Public Service.

[44] The price of wood pellets has been increasing as the wood industry has developed methods of using more of their wastewood, leaving less wood behind to make pellets.

[45] This is the online price for buying an individual bushel. I checked with a large distributor (Specialtgrains) and they gave me an estimate of roughly $5.00 a bushel, including transportation. This would increase the price to $15.80 per million BTUs.

[46] An advertisement for the Magnum 7500 furnace claims that it can achieve up to 87 percent efficiency. If so, the cost per million BTU would decline to $11.50.

More Information about Grass Pellet Cost Estimates

- Unlike the other listed energy sources, there is no current market for grass pellets and the cost per unit has to be estimated; consequently, there is a lot more uncertainty in the price per unit for the grass pellets
- Some factors that would increase the price estimates include: a profit for the farmer or pelleting business, an increase in demand for pellets that causes an increase in input costs, and higher delivery costs if the market is more spread out
- Using RCG pellets instead of SG pellets would increase costs of the raw grass material by roughly 50 percent[51] (RCG has lower yields per acre meaning that more acres would have to be planted)
- Two factors that would reduce the cost estimates include: increased seed productivity which is very likely given historical trends with other crops[52] and the genetic diversity of SG,[53] and improved stove efficiency

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[47] http://grassbioenergy.org/res/fld_res/fld_res_tbl.asp (there was a range depending on the type of grass, I assumed 8100 BTUs per pound).

[48] The cost estimates for the price of the grass are highly dependent on the assumptions made. One study estimates that the price could be between $54 and $146 per ton, with a best estimate of roughly $69.47 (all amounts have been converted to 2005 dollars). M. Duffy and V. Nanhov. "Cost of Producing Switchgrass for Biomass in Southern Iowa." 2001. Another study estimates a similar price of $58.41. A. Hallam, I.C. Anderson, and D.R. Buxton. "Comparative Economic Analysis of Perennial, Annual, and Intercrops for Biomass Production." *Biomass and Bioenergy*. 2001. Taking the average of those prices, I estimate that producing one ton of SG costs $63.94. Some of the harvested grass is lost during the pelleting process. The estimates range from 5-15 percent, and I use the midpoint of 10 percent. R. Samson, M. Drisdelle, L. Mulkins, C. Lapointe, and P. Duxbury. "The Use of Switchgrass Biofuel Pellets as a Greenhouse Gas Offset Strategy." R. Jannasch, R. Samson, A. de Maio, T. Adams, and C. Ho Lem. "Changing the Energy Climate: Clean and Green Heat from Grass Biofuel Pellets." There are different estimates on the cost of pelleting. One study from Canada estimates the cost at $20.14. R. Samson, M. Drisdelle, L. Mulkins, C. Lapointe, and P. Duxbury. "The Use of Switchgrass Biofuel Pellets as a Greenhouse Gas Offset Strategy." 2000. Another study estimates $53.60. J. King. "Reducing Bioenergy Costs by Monetizing Environmental Benefits of Reservoir Water Quality Improvements from Switchgrass Production: Pelletized Switchgrass for Space and Water Heating." The NEGPC cites a charge of $65 by a for-profit company. The average of $46.25 is used here. Finally, I added a packing and delivery charge of $15 a ton.

[49] J. King. "Reducing Bioenergy Costs by Monetizing Environmental Benefits of Reservoir Water Quality Improvements from Switchgrass Production: Pelletized Switchgrass for Space and Water Heating." 1999. I have added in a land cost of $15 per ton.

[50] This is likely an underestimate; see the "More Information" section.

[51] This estimate is based on the climate in Iowa, and in cold-weather climates the RCG might be equivalent in price to SG. See A. Hallam, I.C. Anderson, and D.R. Buxton. "Comparative Economic Analysis of Perennial, Annual, and Intercrops for Biomass Production." *Biomass and Bioenergy*. 2001.

[52] The U.S. Agriculture Department reports that there has been a linear increase in corn yields of about 3-4 percent a year over the past sixty years, resulting in a tripling of yields over that time period. (www.ers.usda.gov/publications/aib786/aib786d.pdf).

[53] There has been comparatively little research done on SG compared to many annual crops, and the potential for increasing SG yields is significant because of the large genetic variation within the species.

- The cost of the raw grass material (12-15 percent of the final price) depends on the yield per acre, and the yield varies significantly depending on climate and soil
- The cost of the grass material could fluctuate and consequently the stability of costs as well as the actual cost is an important consideration
  - Grass supplies could be disrupted by pests,[54] bad weather, or a general failure to establish the crops
- Considering all of the above factors, it is reasonable to think that once the grass pellet market is functioning, grass pellets would probably be comparable in price to other inexpensive heating sources like corn, wood pellets, wood, and natural gas, and it is possible that grass pellets could be slightly cheaper

[54] Neither SG or RCG has many current pests. I. Lewandowski, J. Scurlock, E. Lindvall, M. Christou. "The Development and Current Status of Perennial Rhizomatous Grasses as Energy Crops in the US and Europe. *Biomass and Bioenergy*. 2003.

Appendix

Differences between Reed Canary Grass (RCG) and Switchgrass (SG)

- RCG is a cool-season or "C_3 metabolic pathway" grass; it is most common in wet regions with cool nights and is relatively common in Vermont
- SG is a warm-season or "C_4 metabolic pathway" grass; it is most common in regions with higher temperatures and has a moderate chilling tolerance (some strains have more cold tolerance than others); "the combination of heat, cold, and drought tolerance within the [SG] species results in an adequate level of adaptation for nearly all ecosystems east of the Rocky Mountains and south of the Hudson Bay"[55]
- Both grasses can grow in marginal soils that are not suitable for food crops and both grasses can be cultivated in Vermont:[56] "wherever you can grow corn, you can grow SG"[57]
- SG is less likely to be affected by drought than RCG,[58] although RCG is relatively drought resistant for a C_3 grass[59]
- As a common native species, there is less risk of SG disrupting habitats compared to RCG [60] (see "Environmental Diversity" section on page 4)
- SG uses only about half the water per ton of biomass produced as RCG, so SG typically has a higher yield potential; for example, a multi-site test in the UK found a maximum yield of SG of 6.5 tons/acre while for RCG the maximum yield was 3.4 tons an acre[61]
- However, RCG (as a C_3 grass) tends to perform better in cold climates than SG

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[55] Many strains of SG are susceptible to cold, but other strains have been cultivated in latitudes as far north as Vermont. M.D. Casler, K.P. Vogel, C.M. Taliaferro, and R.L. Rynia. "Latitudinal Adaptations of Switchgrass Populations." *Crop Science*. 2004. p. 293.

[56] http://www.uvm.edu/mastergardener/invasives/alternatives.htm

[57] Roger Samson, REAP Canada.

[58] A. Hallam, I.C. Anderson, and D.R. Buxton. "Comparative Economic Analysis of Perennial, Annual, and Intercrops for Biomass Production." *Biomass and Bioenergy*. 2001.

[59] I could not locate the original study, but a summary was provided in: I. Lewandowski, J. Scurlock, E. Lindvall, M. Christou. "The Development and Current Status of Perennial Rhizomatous Grasses as Energy Crops in the US and Europe. *Biomass and Bioenergy*. 2003. Some strains of SG can also flourish on wetter sites, such as floodplains. RCG thrives on wetter sites and poorly drained soils.

[60] Joy Zedler, Botany Professor at University of Wisconsin-Madison.

[61] IACR Rothamsted. "A Trial of the Suitability of Switchgrass and Reed Canary Grass as Biofuel Crops under UK Conditions." 2005. A study of 18 perennial grasses concluded that SG had the best potential yield. I could not locate the original study, but the review was described in: I. Lewandowski, J. Scurlock, E. Lindvall, M. Christou. "The Development and Current Status of Perennial Rhizomatous Grasses as Energy Crops in the US and Europe. *Biomass and Bioenergy*. 2003. One review stated "The C4 grasses switchgrass and miscanthus are, on those locations which are suitable for their production, the best grasses to produce biomass as solid biofuel because they best combine high biomass yields with good combustion characteristics of the biomass." I. Lewandowski, J. Scurlock, E. Lindvall, M. Christou. "The Development and Current Status of Perennial Rhizomatous Grasses as Energy Crops in the US and Europe. *Biomass and Bioenergy*. 2003. p. 22.

and tests would have to be conducted to determine which grass yields more in a particular climate; as a cold season grass, RCG may be better adapted for New England[62]

- SG production uses less energy (and thus less fossil fuels) than RCG production[63]
- The more water a grass intakes the more minerals it intakes as well (since water contains minerals); these minerals are a major component of ash, and consequently SG typically has much less ash, nitrogen and potassium than RCG[64]
    - Ash is problematic for emission and stoves, as many current stoves cannot handle ash content greater than 3 percent,[65] although newer stoves may be able to handle higher ash contents
    - Delayed harvesting decreases the water content of grass (beneficial for combustion), and also allows ash components like potassium and chlorine to be leached out
- The bioenergy potential of SG has been studied much more extensively in the United States, although RCG has been studied extensively in Europe, especially the Scandinavian countries
- RCG quickly forms a thick canopy reducing the number of weeds and the need for herbicides
- The NEGPC report assumes that RCG would be used due to the Vermont cold climate (p. 26); given that SG has potentially higher yields (less cost) and that RCG presents invasive species problems, it may be worthwhile to determine whether there are strains of SG that can be productively cultivated in Vermont

[62] "Reed canary grass is the lowest yielding of the most important biomass grasses, but it is the only grass that can be produced in regions with short vegetation period and cold winters such as northern Europe." I. Lewandowski, J. Scurlock, E. Lindvall, M. Christou. "The Development and Current Status of Perennial Rhizomatous Grasses as Energy Crops in the US and Europe. *Biomass and Bioenergy*. 2003. p. 22.

[63] RCG needs to be planted more often and also has a lower yield, thus it uses more carbon and energy. M. Bullard and P. Metcalfe. "Estimating the Energy Requirements and CO_2 Emissions from Production of the Perennial Grasses: Miscanthus, Switchgrass, and Reed Canary Grass." 2001.

[64] Roger Samson, Patrick Duxbury, and Lindsey Mulkins. "Research and Development of Fibre Crops in Cool Season Region of Canada." 2004. I. Lewandowski, J. Scurlock, E. Lindvall, M. Christou. "The Development and Current Status of Perennial Rhizomatous Grasses as Energy Crops in the US and Europe. *Biomass and Bioenergy*. 2003.

[65] High ash content leads to the formation of "clinkers" or chunks of fused minerals that can clog stoves.