Global Carbon Impacts of Using Forest Harvest Residues for District Heating in Vermont

Howard A. McLain, Oak Ridge National Laboratory, Oak Ridge, TN

ABSTRACT

Forests in Vermont are selectively logged periodically to generate wood products and useful energy. Carbon remains stored in the wood products during their lifetime and in fossil fuel displaced by using these products in place of energy-intensive products. Additional carbon is sequestered by new forest growth, and the forest inventory is sustained using this procedure. A significant portion of the harvest residue can be used as biofuel in central plants to generate electricity and thermal energy, which also displaces the use of fossil fuels. The impact of this action on the global carbon balance was analyzed using a model derived from the Graz/Oak Ridge Carbon Accounting Model (GORCAM).

The analysis showed that when forests are harvested only to manufacture wood products, more than 100 years are required to match the sequestered carbon present if the forest is left undisturbed. If part of the harvest residue is collected and used as biofuel in place of oil or natural gas, it is possible to reduce this time to about 90 years, but it is usually longer. Given that harvesting the forest for products will continue, carbon emission benefits relative to this practice can start within 10 to 70 years if part of the harvest residue is usually higher for electric generation plants, but it can be reduced substantially by converting to cogeneration operation. Cogeneration makes possible a ratio of carbon emission reduction for district heating to carbon emission increase for electricity generation in the range of 3 to 5. Additional sequestering benefits can be realized by using discarded wood products as biofuels.

Introduction

Vermont has a long tradition of using wood for its space heating needs. However, in recent years, wood has lost favor to oil for this purpose. More than 75% of the state is forested, and the use of this indigenous source to meet energy needs is being encouraged by the state for economic and environmental reasons.

District heating and cooling is an existing technology that converts energy into heated or chilled water, or steam, at a central plant and distributes it to the consumers through pipe networks. For heating, the central plant can be either a heating-only plant or a cogeneration plant producing both electricity and useful thermal energy. Cogeneration plants have the potential of using the fuel more efficiently.

Vermont has set up a study team to identify the barriers that are keeping biomass district heating technology from reaching its full potential, and to collect and disseminate the information on the technology and the market in Vermont and elsewhere. A key issue is the impact of wood-fired district heating systems on the CO_2 buildup in the atmosphere. There are major concerns about the effect of this buildup on the earth's climate, and nations are being encouraged to reduce it (Bolin 1998). Forests play an important role in this process, providing biofuels that add CO_2 to the atmosphere, but also balancing this by vegetation growth that removes CO_2 from the atmosphere.

The investigation reported in this paper is aimed at evaluating carbon impacts on the atmosphere by actual biofuel district heating systems being installed or being proposed in Vermont. The biofuel is wood chips derived from forest harvest residues and wood product manufacture waste. The study focuses on three applications: (1) using biofuel boilers to displace oil boilers in two different district heating systems, (2) converting an existing biofuel 50-MWe electric plant to supply hot water to an existing district heating

system now using oil and natural gas boilers, and (3) installing a new small biofuel cogeneration system in one of the state's ski resort areas.

Evaluation of these systems' biofuel carbon impacts must include analysis of forest management procedures to account for the temporal changes in the carbon content of the forest components and of the harvested materials (Schlamadinger and Marland 1996). Carbon sequestration impacts were evaluated using a Fortran program derived from the relations used by Schlamadinger and Marland in their spreadsheet model, called the Graz/Oak Ridge Carbon Accounting Model (GORCAM) (Schlamadinger and Marland 1996; Schlamadinger et al. 1996). The primary difference between the Fortran program and GORCAM is the use of an empirical forest growth relation, developed from the data of Birdsey (1996a, 1996b). For convenience, the carbon flows and inventories in the model are described in terms of elemental carbon, recognizing the organic forms in the forests and products and CO_2 , CH_4 , etc. in the atmosphere.

Vermont Forests

Most of Vermont's forests are second-growth forests, composed predominately of about 60% northern hardwoods and 40% softwoods. They typically have 63.4 MgC/ha and grow to 76.4 MgC/ha when they are selectively harvested. Trees are harvested for wood products and biofuels about every 10 years, and 9.5 MgC/ha are cut during each harvest (Maker and DeGeus 1997). The trend in the state is now towards having sustainable forest management, where new natural tree growth matches or exceeds the wood harvested for products or biofuels.

Birdsey estimated the carbon storage for major forest types in the conterminous United States and published the data in the form of tables. For the northeastern United States, data are included for maple-beech-birch, white/red pine, and spruce-fir forests (Birdsey 1996a, 1996b). For our analysis, data for forests after the final clearcut harvests were combined (60% maple-beech-birch and 40% white/red pine), and two empirical correlations were developed. The first correlation is for the total carbon in standing trees and woody roots (0.161 of the total). Woody roots left in the ground after trees were cut are assumed to be woody litter. The second correlation is for the ground surface litter. The first-order-reaction decay constant for the woody litter above and below ground was estimated to be 0.054 yr^{-1} from the information published by Birdsey. The carbon stored in the understory vegetation was ignored for our analysis, since it is small (about 2 MgC/ha) compared to the total tree storage of interest here.

A large portion of the carbon in Northeast forests is in the top meter of the forest soil. It includes the fine tree roots, but excludes the coarse woody roots. For the forests being considered, Birdsey estimated that this component has a constant value of 163 MgC/ha. This implies that gains and losses in the soil carbon nearly balance.

The Model

The structure of the carbon balance model used in this study is presented in Fig. 1. It is an adaptation of that for the GORCAM model (Schlamadinger and Marland 1996; Schlamadinger et al. 1996). Carbon storage can be visualized as being in three general categories: (1) the forest, (2) wood products and biofuels, and (3) displaced fossil fuels. Storage of carbon in the forest itself is discussed above. Carbon in the products and fuels made from the harvested vegetation remains sequestered until they decay or are burned. Furthermore, wood products generally require less energy in their manufacture than products made of more energy-intensive materials, such as metals and polymers. This and the displacement of fossil fuel in heating and power plants allow the retention of the carbon accumulated in the fossil fuel since prehistoric times.



Figure 1. Carbon flow model (modification of Schlamadinger et al. 1996)

However, penalties are included in this model for fossil fuels to manage and harvest the forests, and for the transport of wood products and fuels.

The basic carbon flow balances used in the model are described by the Schlamadinger and Marland papers referenced above. Their original model used a simple relation describing forest growth. This was later refined using alternate forest growth relations, including relations published to describe the detailed behavior of carbon flow in forest soil and litter (Dewar 1991) and to account for the recycling and landfill of discarded products. For the model presented here, the forest growth relations were replaced by the empirical correlations described above. In these relations, carbon stored in forest soil is invariant. Since carbon lost from the soil to the atmosphere is replaced by part of the carbon lost from the forest litter and roots, we assumed that all of the carbon lost by the decay of litter and roots flows directly to the atmosphere.

The primary purpose for wood harvest is the generation of wood products and biofuels. The portions of the harvest not used for these purposes are left as residue in the forest. Wood products are classified as long-lived, short-lived, and very short-lived. Long-lived products are used as building materials and furniture and are assumed to have a 80-year weighted mean lifetime. Short-lived products are used as telephone poles, pallets, etc., and are assumed to have a 20-year life. Very short-lived products are pulp and paper, which are assumed to have 1-year life (Schlamadinger and Marland 1996). For this analysis, fractions of harvested trees were assumed to be typical values for Vermont: 0.365, 0.161, and 0.069 for long-lived, short-lived, and very short-lived products, respectively (Maker and DeGeus 1997).

Wood products either decay to the atmosphere or are discarded. Discarded products can be recycled into other products, landfilled, or burned. Recycled products are lumped in with the original products in this study. Landfilled products have finite lifetimes, which were assumed to be 40, 10, and 1 years for the long-lived, short-lived, and very short-lived products, respectively. Discarded products can be used as biofuels to displace fossil fuels in energy conversion plants. Landfilled wood decays into CO_2 and CH_4 . We did not account for the higher impact that CH_4 has in blocking radiative heat loss from the earth (Micales and Skog 1997).

If the forest is harvested for products only, the remainder of the harvest not used for products is left in the forest to decay. However, when there is a biofuel market, as in Vermont, typically an additional 0.255 fraction of the harvest is removed for that use (Maker and DeGeus 1997). We assumed that the biofuel has a higher heating value of 40.23 GJ/MgC.

An important part of the model is the relation of carbon emissions for wood products and biofuels compared to those for alternative products and fossil fuels. The model uses parameters, called *displacement factors*, to describe the carbon retained in unused fossil fuels and wood products. Following the convention of Schlamadinger and Marland, they are called *energy displacement factors* and *product displacement factors*. Relations for calculating these factors are given by Schlamadinger and Marland. The values of the product displacement factors were assumed to be 0.5 for the long-lived products, 0.25 for the short-lived products, and 0.25 for the very short-lived products.

Energy displacement factors, D_{f} are defined as the ratio of the carbon emissions from a fossil-fueled plant to those from a wood-fueled plant having the same capacity. Or, in other words (Schlamadinger and Marland 1996),

| $D_f =$ | <u>C emission per J fossil fuel</u> × | < | Efficiency of biofuel boiler |
|---------|---------------------------------------|---|----------------------------------|
| | C emission per J biofuel | | Efficiency of fossil fuel boiler |

Values of D_f are listed in Table 1. Fuel carbon emissions are 13.7 kgC/GJ for natural gas, 19.2 kgC/GJ for distillate oil, and 24.9 kgC/GJ for wood (Marland and Pippin 1990; Mitchell 1990).

Emission factors accounting for the fossil fuel emissions for forest management, for harvesting and transporting the biofuels, and for the "upstream" extraction and transporting of the displaced fossil fuels are also included in the model.

The Scenarios

The scenarios selected for analysis are listed in Table 1. They represent actual situations or situations being considered in Vermont. The table lists capacities and efficiencies of both the biofuel and the fossil fuel plants being displaced. For plants supplying heat to district heating systems, the efficiencies do not include losses in the thermal distribution systems, since they are assumed to exist for either type of heat source.

Except for the last two scenarios, electricity generated in biofuel plants is assumed to displace that generated by natural gas turbine or combined-cycle plants. Much of the base load electricity in the New England area is generated in hydro and nuclear plants. Natural gas combined-cycle plants, having about 50% higher heating value (HHV) efficiency, are finding favor for additional base load and intermediate-load electrical generation. For additional peak load capacities, gas turbine plants having about 33% HHV efficiency are being installed (Holcomb 1998).

- Scenarios 1 and 2 are for heating-only boilers supplying heat to district heating systems. Oil is the prevalent fuel for larger heating systems in Vermont. The efficiencies of oil vs wood-fueled boilers are about the same (Maker and DeGeus 1997).
- Scenario 3 is an existing wood-fired steam plant generating electricity. When built, it was used as a base load plant, but it is now being used for peak loads. Reductions of carbon emissions relative to emissions from both types of gas turbine plants were estimated.
- Scenario 4 is the conversion of the existing wood-fired plant to cogeneration operation, supplying medium-temperature (150–175°C) hot water to an existing district heating system. Heat for the district system is now suppled by boilers fueled by a mix of 75% natural gas and 25% oil. In this scenario, the electrical capacity of the cogeneration plant is reduced, but its overall efficiency is increased. Calculations were done for the plant operating at peak thermal load the entire year and at the expected annual average thermal load.
- Scenario 5 is a repeat of Scenario 3 assuming that the biofuel plant uses integrated gasifier combinedcycle technology now being developed. This plant has a 40% conversion efficiency, which is the goal of this technology's development program (Downing 1998).
- Scenario 6 is a repeat of the Scenario 4 cogeneration plant using integrated gasifier combined-cycle technology to generate electricity and supply low-temperature (80–120°C) hot water to the district heating system. A demonstration plant using this technology has a reported 33% electrical generating efficiency and 83% overall efficiency (Yan et al. 1997). Biofuel plants typically have high water vapor content in the flue gases. For this cogeneration plant, over 20% of the heat recovered is by water vapor condensation.
- Scenario 7 is for a relatively small (10 MWe) turbine generating plant in a ski resort area. There is a critical need for additional electricity during the skiing season, and the main electric transmission network serving the area is operating at its capacity. Upgrading this network would be very expensive and undesirable, and the installation of the small generation plant is being considered. It is likely that this plant's fuel would be oil (Maker and DeGeus 1997).
- Scenario 8 expands on the Scenario 7 turbine generating plant, recovering part of the heat from the turbine exhaust gas for use in a large hotel-restaurant-retail shop complex being planned for the area. The heat demand for this complex is assumed to be 2.9 MWt.

Table 1. Summary of carbon emission reductions for selected scenarios

| | | | | | | | _ | Relative to | Harvest |
|--|------------------|--------------|------------|-------------------------------|--------------------|------------|--------------|-------------------|----------|
| | | | | | | | | tor Products Only | |
| | Plant Canacities | | Plant* | Displaced Plant* | | | Displacement | Brookovon | 100 Year |
| Biofuel Plant Scenario | (MWt) | (MWe) | Efficiency | Туре | Fuel | Efficiency | | Time (year) | (GgC) |
| 1. Capital complex heating system | 4.4 | | 0.65 | Boiler | Oil | 0.65 | 0.774 | 9 | 14 |
| 2. Small institution heating system | 2.1 | | 0.65 | Boiler | Oil | 0.65 | 0.774 | 9 | 7 |
| 3. Boiler/steam turbine electric | - | 50.0 | 0.25 | Turbine | Gas | 0.33 | 0.418 | 42 | 337 |
| | | | | Combined-cycle | Gas | 0.50 | 0.276 | 73 | 96 |
| Boiler/steam turbine cogen Medium-temp hot water heating | | | | Heating plant boilers | 75% Gas 25% Oil | 0.80 | | | |
| a.1. Peak load** | 52.7 | 41.0 | 0.47 | Turbine | Gas | 0.33 | 0.543 | 26 | 550 |
| a.2. | | | | Combined-cycle | Gas | 0.50 | 0.426 | 40 | 350 |
| b.1. Annual average load | 22.7 | 4 6.1 | 0.35 | Turbine | Gas | 0.33 | 0.480 | 33 | 444 |
| b.2. | | | | Combined-cycle | Gas | 0.50 | 0.346 | 54 | 214 |
| 5. Gasifier/combined-cycle electric | | 50.0 | 0.40 | Combined-cycle | Gas | 0.50 | 0.442 | 38 | 222 |
| 6. Gasifier/combined-cycle cogen Low-temp hot water heating | | | | Heating plant boilers | 75% Gas 25% Oil | 0.80 | | | |
| a. Peak load** | 61.9 | 41.3 | 0.83 | Combined-cycle | Gas | 0.50 | 0.740 | 12 | 558 |
| b. Annual average load | 22.9 | 47.2 | 0.55 | Combined-cycle | Gas | 0.50 | 0.555 | 25 | 360 |
| 7.a. Ski resort gasifier/turbine elect*** | | 10.7 | 0.30 | Turbine | Gas | 0.33 | 0.502 | 30 | 34 |
| b. | | | | Turbine | Oil | 0.31 | 0.703 | 14 | 59 |
| 8. Ski resort gasifier/turbine elect*** with heat recovery | 2.9 | 10.7 | 0.38 | Turbine with heat recovery | Oil | 0.39 | 0.708 | 13 | 60 |

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* Plant efficiences based on fuel higher heating value.
** Plant assumed to operate at maximum thermal load the entire year.
*** Plant assumed to operate 40% of the year.

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For Scenario 3, a biofuel steam plant displacing electricity generated by gas turbine plant, D_f is 0.418. Converting this plant to cogeneration operation (Scenario 4) results in D_f being 0.543 at peak thermal load. At these conditions, the electrical portion of D_f is reduced from 0.418 to 0.343, but the thermal load adds 0.200. This implies a cogeneration emission advantage ratio of 0.200/0.075, or 2.7. If the steam plant displaces electricity generated by a gas combined-cycle plant, the advantage ratio is 4.0. For the integrated gasifier/combined cycle plant, this ratio is 4.9.

The Results

The impact of using part of the forest harvest by-products on carbon sequestering in Scenarios 1 and 2 is presented in Fig. 2. Plot (a) represents harvesting the forest for products only, and plot (b) represents harvesting it for products and biofuel. The results are normalized as MgC per 100 ha. The initial condition for the analysis is a uniform forest having 76.4 MgC/ha standing trees (including the woody roots). Each 0.1 year, 9.5 MgC of trees are cut from 1 ha of forest until 100 ha have been selectively harvested by the end of 10 years. The harvest procedure is then repeated. The upper curve in the plots is the carbon accumulation in the forest if it is left undisturbed.

The analysis indicates that the periodic selective harvest procedure does meet Vermont's goal of maintaining a sustainable forest in the state. Much of the harvested carbon is accumulated in wood products, particularly long-lived products, and carbon is also retained in fossil fuels not consumed by using products made of wood instead of those made of energy-intensive materials. But more than 100 years are required for carbon in the products, the displaced fossil fuel, and the harvested forest to match that accumulated in a forest left undisturbed.

If part of the harvest litter and wood waste from product manufacture are used as biofuels, the retention of carbon in the displaced fossil fuel for energy conversion reduces the breakeven time, the time for accumulated carbon of the harvested forest to match that in an undisturbed forest. For the first two scenarios, it is 92 years, which is still a long time, but certainly less than that for the forest harvested for products only.

Figure 3 is a plot illustrating the differences in the carbon accumulations in the two plots in Fig. 2. It shows the reduction of the carbon stored in the harvest waste and the gain in the carbon retained in the displaced fossil fuel. The breakeven time for using part of the litter as biofuel is about 9 years, and the net gain in the accumulated carbon at the end of 100 years is about 1500 MgC/ha.

Because it is assumed in this analysis that the product mix is the same for all scenarios and no discarded products are used as biofuels, breakeven times for carbon accumulation relative to a forest being harvested for products only and to a forest not harvested are functions of D_f as illustrated in Fig. 4. Furthermore, the net gain in stored carbon relative to a forest harvested for products only is a linear function of D_f having a slope of 2618.9 MgC/100 ha and an intercept of -569.0 MgC/100 ha. The same relation applies to the stored carbon relative to an unharvested forest, except that it has an intercept of -1771.2 MgC/100 ha.

The values of D_f and accumulated carbon breakeven times when using harvest residue as biofuel relative to not using it for the selected scenarios are summarized in Table 1. The first two scenarios were addressed in the discussion for Fig. 2.

For the existing power plant (Scenario 3), D_f is low and the breakeven time is high because of the plant's low energy-conversion efficiency. These values are improved in converting the plant to cogeneration operation to supply heat to the nearby district heating system (Scenario 4). Values are listed in Table 1 for the district heating system load factor being at its peak the entire year and for its being at its 0.43 annual average (Maker and DeGeus 1997). The values listed are for the displaced heating plant using a 75% gas,



Figure 2. Cumulative carbon sequestration for 100 ha forest harvested at an uniform rate for (a) products only and for (b) products and biofuels. The upper curve in both plots is the carbon sequestered if the forest is left unharvested. Plot (b) is for Scenarios 1 and 2, $D_f = 0.774$.



Figure 3. Differences in the carbon accumulation values presented in Fig 2. for 100 ha forest harvested at an uniform rate for products and biofuels and for products only. Plot is for Scenarios 1 and 2, $D_f = 0.774$.



Figure 4. Breakeven times required for cumulative carbon sequestered in 100 ha of forest harvested at an uniform rate for products and biofuels to exceed that in a forest left undisturbed and that in a forest for products only. Breakeven times are displayed as functions of the energy displacement factor, D_f . Product displacement factors assumed to be 0.50, 0.25, 0.25 for long-lived, short-lived, and very short-lived products, respectively.

25% oil fuel mix. If the displaced plant uses only oil (Scenario 4.b.1), D_f and breakeven time values would become 0.504 and 29 years, respectively.

Improved technology can benefit CO_2 emission control significantly. Replacing the existing biofuel electric plant with one using integrated gasifier/combined-cycle technology (Scenario 5) shortens the breakeven time from 73 years to 38 years. Conversion of this improved technology plant to cogeneration operation, with heat supplied to a low-temperature hot water system (Scenario 6), shows additional improvement and shortens the breakeven time to 25 years. A low-temperature hot water district heating system was specified for this case because of its ability to recover the flue gas water vapor heat of condensation for the heating system.

Scenario 7 represents a somewhat unique situation in Vermont. A local 10-MWe electric generation plant is being considered for one of the ski areas, and a reasonable choice appears to be an oil-fired turbine having 31% efficiency. This unit would run during the winter skiing season, about 40% of the year. If an integrated gas biofuel gasifier/turbine plant with about 30% efficiency were installed instead, D_f for the plant would be 0.703 and the carbon savings breakeven time would be 14 years. The benefit would not be as great for a natural gas turbine plant, but the cost of supplying compressed natural gas to the plant appears to be greater than for oil (Maker and DeGeus 1997).

The addition of a heat recovery unit to the ski area gas turbine plant to serve the heating demands of a large recreation complex would increase the plant's efficiency. If the unit was added to either the natural gas turbine or the biofuel gasifier turbine (Scenario 8), there would be little change in D_f and the breakeven time from the values for Scenario 7, but the amount of carbon emission savings would be greater.

The 100-year carbon emission savings that could be realized by using wood-chips derived from periodic forest harvests instead of oil or natural gas are summarized in the last column of Table 1. As expected, greater emission savings are predicted for the larger-capacity plants that have higher efficiencies. These values were calculated assuming 9.5×0.255 , or 2.42 MgC chips per ha harvested and assuming that these chips have a 40.23 GJ/MgC HHV. For the first six scenarios, except for 4.a and 6.a, we assumed a thermal load factor of 0.43, the value for the district heating system being connected to the existing power plant in Scenario 4. The thermal load factor was assumed to be 1.0 for Scenarios 4.a and 6.a to see the effect of operating the plant at peak thermal load the entire year. The plant load factor for the last two scenarios was assumed to be 0.4.

For Table 1, we assumed that 50% of the discarded products were placed into a landfill and that none of these materials were used as biofuels. The calculation for Scenarios 1 and 2 was repeated assuming that 25% of the discarded products were put into the landfill and another 25% of the material was used as biofuel, with the results presented in Fig. 5. As the quantity of the wood products increases with time, the amount that is discarded also increases with time. This increases the availability of biofuels, from 2.42 MgC/ha harvested at the start of operation to 3.45 MgC/ha at 50 years, and to 3.70 MgC/ha after 100 years. This implies that a larger wood-fueled energy conversion industry could be supported as the discarded products are used as biofuels.

The increased use of biofuels is at the expense of the carbon stored in the landfills. Overall, there is a net gain, since the reduction in the fossil fuel emissions more than offset the loss of the landfill carbon for these scenarios. Per 100 ha of forest, the discarded carbon in the landfill is reduced by 119 MgC at 50 years and 228 MgC at 100 years, but the cumulative fuel emission savings are increased by 276 MgC and 736 MgC, respectively. These values are conservative, since they do not include the detrimental effect of CH_4 generated by the anaerobic decomposition of the landfilled wood.



Figure 5. Cumulative carbon sequestration for 100 ha forest harvested at an uniform rate for products and biofuels with 25% of the discarded products used as additional biofuel. Plot is for Scenarios 1 and 2, $D_f = 0.774$.

Conclusions and Recommendations

The analysis shows that using part of the forest harvest residue for district heating in Vermont has a positive impact on reducing the amount of carbon discharged to the atmosphere. Fuel oil is the most common heating medium in the state, and use of biofuels in efficient conversion plants resulted in the greatest savings.

Using the selective harvesting procedure, the state can sustain, or increase, its large forest inventory. If these forests were left undisturbed, much greater amounts of carbon could be sequestered over the next 100 to 150 years. However, for economic benefits, it is likely that the forests will continue to be harvested for products. This analysis shows that a large part of the carbon lost by cutting the trees is made up for by the carbon stored in the products and the fossil fuel not used when wood is used in products in place of more energy-intensive materials.

The use of part of the harvest residue as biofuel can make up for most of this difference. Replacing fuel oil heating systems with higher-efficiency biofuel systems can reduce the time needed to match the sequestered carbon in unharvested forests to about 90 years. Shorter times could be realized if some of the discarded wood products are used as biofuels in efficient heating systems. Carbon emission savings for the existing 50-MWe wood-fired electricity generation plant are positive, but they are not nearly as good as those for systems displacing oil-fired heating plants. This is because of the relatively low efficiency of the electricity plant and the fact that its generated power displaces power that is generated in a gas-fired turbine or a combined-cycle plant. Converting the electricity generation plant to cogeneration for district heating has a very positive impact. Thermal energy generated in the

plant replaces that generated in high-efficiency boilers fueled by a mix of gas and oil. Although smaller than the savings for dedicated wood-fired heating plants replacing oil-fired plants, the savings are still positive.

New biofuel integrated gasifier/combined-cycle technology now being developed promises about 50% improvement in plant efficiencies and carbon emission savings. Cogeneration plants are reported to have up to 83% efficiencies when generating low-temperature hot water. Application of the new technology to replace the small oil-fired turbine cogeneration plant being considered for the Vermont ski area could result in large emission savings.

In most cases, there is some sacrifice of electric generation plant capacity when converting to cogeneration operation, but there is a large gain in recovered useful energy. The ratio of carbon emission savings for district heating to that gained for electrical generation is in the range of 3 to 5.

Considerable effect was directed to obtaining representative forest growth data for this study. We recognize that there is variability among forests and that there is room for improvement in the understanding of carbon dynamics within forests. Only part of the residue is removed from the harvested forests for biofuel, but there is some question about the effect of this on the forest nutrient balance and subsequent forest growth rate (Borjesson et al. 1997). This investigation should be expanded to determine the sensitivity of the carbon emission savings to these uncertainties.

While our investigation of the impact of using a part of the discarded wood products as biofuel was very limited, our calculations showed that this action improved the carbon emission savings. The effect of using the discarded products as biofuel should be studied more extensively. This study should include as one of its parameters the impact of methane generated during landfilled wood product decomposition.

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