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How To Estimate Recoverable Heat Energy in Wood or Bark Fuels

ABSTRACT

A reference source is provided for estimating the amount of heat energy that may be recovered using wood or bark fuel in typical furnace and boiler or hot air combustion heat recovery systems. A survey of reported data on higher heating values for various species of wood and bark fuels i’s provided. A set of formulas of a type commonly used by combustion technologists is also provided for estimating combustion system heat losses and net recoverable heat energy per pound of fuel as-fired, based on fuel higher heating value, moisture content, and excess air stack gas temperature, and ambient temperature assumptions.

FOREWORD

The value of wood or bark fuel in relation to direct combustion heat recovery systems depends on the amount of heat energy that can be recovered. Economic analyses of direct combustion utilization of wood or bark should be based on estimates of recoverable heat energy. This report provides information and formulas which can be used to derive estimates of recoverable heat energy in wood or bark fuels.

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HOW TO ESTIMATE RECOVERABLE HEAT ENERGY IN WOOD OR BARK FUELS

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INTRODUCTION

Wise utilization of the forest resource relates to awareness of its value. Fuel value of wood or bark depends on the amount of heat energy that can be recovered. The amount of recoverable heat energy varies with moisture content and chemical composition. Recoverable heat energy varies among tree species and even within a species.

Information about wood and bark fuel is available from various sources (*5,9-11,13,14,17-19*).[2] Procedures and formulas for estimating the heating value of fuels are given in engineering texts and handbooks (*6,12*), and have long been used and are common knowledge to many combustion engineers and technologists. This is a summary of information which may be used to estimate recoverable heat energy in wood or bark fuel.

Formulas are provided for calculating approximate recoverable heat energy of wood or bark fuel, and may be adapted for a computer program or used with a pocket calculator. The information and formulas are intended for studies of resource potential, economic studies, and generalized fuel value comparisons, but not for determining thermal efficiency of particular boilers or heat recovery systems. Standardized techniques for determining thermal efficiency or heat output in a given heat recovery system are described elsewhere (*16*).

RECOVERABLE HEAT ENERGY

In any combustion heat recovery system, some of the heat of combustion escapes from the system in flue or “stack” gases. Heat in stack gases is not recoverable once it gets past heat recovery devices of the system. The amount of heat which escapes in stack gases depends on design of the system, method and skill of operation, and fuel quality. Factors which influence the amount of escaping heat are fuel moisture content, hydrogen content, quantity of excess air admitted to the furnace, and temperature of stack gases beyond all heat recovery devices of the system. Additionally, some heat is lost because of thermal radiation, convection, and other causes. Total heating capacity of the combustion system, and amount of wood or bark fuel which can be burned, are also dependent on system design, skill of operation, and the quality of the fuel.

Estimating recoverable heat energy for wood or bark fuel requires information regarding the temperature of air and fuel entering the furnace, temperature of stack gases beyond heat recovery devices, fuel moisture content, percent excess air, and the ovendry heat of combustion, or “higher heating value” of the fuel. Estimated higher heating values for some species are presented (table 1). However, recoverable heat energy can be estimated only after stack gas heat and other heat losses are estimated. The amount of recoverable heat energy per pound of fuel is always somewhat less than higher heating value. Higher heating value is never the amount of heat actually recovered, because of fuel moisture content and unavoidable escape of heat in stack gases, and other heat losses. Heat which is not lost or does not escape in stack gases is assumed to be recovered for useful purposes, such as production of process steam, for example.

Moisture Content

Fuel moisture content is usually reported as the wet weight basis moisture content. Moisture content expressed on a wet weight basis (also called “green” or “as fired” moisture content) is the decimal fraction of fuel that consists of water. For example, a pound of wet wood fuel at 50 percent moisture content contains 0.50 pound of water and 0.50 pound of wood. Note that the wet weight basis differs from the dry weight basis method of expressing moisture content which is more commonly used for describing moisture content of finished wood products.

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[1] Maintained at Madison, Wis., in cooperation with the University of Wisconsin.

[2] Italicized numbers in parentheses refer to literature cited at end of report.

Table 1.—Higher heating value for some wood and bark species as reported in other publications[1]

Species	Higher heating value	Species	Higher heating value
	Btu / ovendry lb		*Btu / ovendry lb*
		WOOD	
Bigleaf maple	8,400 (*7*)	Red alder	8,000 (*20*)
Bigleaf maple	8,410 (*20*)	Red oak	9,360 (*3*)
Black cottonwood	8,800 (*7*)	Redwood	9,210 (*1*)
Cypress	10,660 (*3*)	Sitka spruce	8,100 (*7*)
Douglas-fir	9,200 (*7*)	Western hemlock	8500 (*7*)
Douglas-fir	8,860 (*8*)	Western hemlock	8,000 (*20*)
Douglas-fir	8,800 (*20*)	Western hemlock	8,620 (*1*)
Douglas-fir	8,910 (*1*)	Western redcedar	9,700 (*7*)
Hickory	9,360 (*3*)	Western redcedar	9,700 (*20*)
Lodgepole pine	8,600 (*7*)	White ash	9,630 (*3*)
Oregon ash	8,200 (*20*)	White birch	9,340 (*3*)
Oregon white oak	8,110 (*20*)	White cedar	9,070 (*3*)
Pitch pine	12,230 (*3*)	White fir	8,300 (*7*)
Ponderosa pine	9,100 (*7*)	White fir	8,000 (*20*)
Ponderosa pine	9,140 (*20*)	White oak	9,510 (*3*)
Poplar	9,630 (*3*)	White pine	9,610 (*3*)
Red alder	8,000 (*7*)	Yellow pine	10,380 (*3*)
		BARK	
American beech	7,993 (*10*)	Northern black cottonwood	8,765 (*10*)
American elm *Ulmus americana*	7,385 (*2*)	Northern red oak	8,896 (*9*)
American sycamore *Platanus occidentalis*	7,877 (*2*)	Northern red oak *Quercus rubra*	8,383 (*2*)
Balsam fir	9,339 (*9*)	Northern white oak	7,536 (*9*)
Balsam fir *Abies balsamea*	9,437 (*2*)	Northern white oak *Quercus alba*	7,450 (*2*)
Balsam (all varieties)	9,100 (*15*)	Paper birch *Betula papyrifera*	9,887 (*2*)
Beech	7,640 (*15*)	Pin oak	8,883 (*10*)
Black cottonwood	9,000 (*7*)	Ponderosa pine	9,616 (*9*)
Black gum *Nyssa sylvatica*	8,412 (*2*)	Poplar	8,810 (*15*)
Black oak	8,340 (*10*)	Post oak	6,773 (*10*)
Black spruce	9,143 (*10*)	Quaking aspen	8,712 (*9*)
Black spruce	8,610 (*15*)	Quaking aspen *Populus tremuloides*	8,897 (*2*)
Black spruce *Picea mariana*	8,782 (*2*)	Red alder	8,760 (*10*)
Black tupelo	8,102 (*10*)	Red alder *Alnus rubra*	8,410 (*2*)
Black willow	8,137 (*10*)	Red maple	8,293 (*10*)
Black willow *Salix nigra*	7,648 (*2*)	Red pine	9,070 (*9*)
Douglas-fir	9,400 (*4*)	Red spruce	8,630 (*15*)
Douglas-fir	10,100 (*7*)	Shagbark hickory	8,423 (*10*)
Douglas-fir	10,100 (*20*)	Shortleaf pine	9,319 (*9*)
Douglas-fir	9,962 (*9*)	Shortleaf pine *Pinus echinata*	9,550 (*13*)
Eastern cottonwood	8,422 (*9*)	Silver maple	8,360 (*10*)
Eastern hemlock	8,890 (*15*)	Slash pine	9,327 (*9*)
Eastern hemlock	9,517 (*10*)	Slash pine	9,380 (*13*)
Eastern hemlock *Tsuga canadensis*	9,348 (*2*)	Southern red oak	8,371 (*9*)
Eastern white pine	9,647 (*10*)	Spruce pine *Pinus glabra*	8,705 (*13*)
Elm (soft)	7,600 (*15*)	Spruce pine *Pinus glabra*	8,595 (*13*)
Engelmann spruce	8,830 (*9*)	Spruce pine *Pinus glabra*	8,550 (*13*)
Engelmann spruce *Picea engelmannii*	8,820 (*2*)	Sugar maple	8,426 (*9*)
Green ash	8,367 (*10*)	Sugar maple	8,230 (*15*)
Jack pine	9,393 (*9*)	Sugar maple *Acer saccharum*	7,739 (*2*)
Jack pine	8,930 (*15*)	Sweetgum	7,650 (*9*)
Jack pine *Pinus banksiana*	9,339 (*2*)	Sweetgum *Liquidamber styraciflua*	7,912 (*2*)
Loblolly pine	9,320 (*9*)	Sycamore	7,978 (*10*)
Loblolly pine *Pinus taeda*	9,400 (*13*)	Tamarack	9,010 (*15*)
Lodgepole pine	9,382 (*9*)	Virginia pine	9,170 (*9*)
Lodgepole pine *Pinus contorta*	10,760 (*2*)	Western hemlock	8,900 (*4*)
Longleaf pine	9,290 (*9*)	Western hemlock	9,800 (*7*)
Longleaf pine *Pinus palustris*	9,130 (*13*)	Western hemlock	9,297 (*9*)

Table 1.— Higher heating value for some wood and bark species as reported in other publications[1]-continued

Species	Higher heating value	Species	Higher heating value
	Btu / ovendry lb		*Btu / ovendry lb*
	BARK		
Western larch	8,825 (9)	White spruce	8,913 (9)
Western larch *Larix occidentalis*	8,750 (2)	White spruce	8,530 (15)
Western redcedar	8,700 (7)	Yellow birch	9,200 (15)
White ash	8,453 (10)	Yellow birch *Betula alleghaniensis*	9,548 (2)
White birch	10,332 (9)	Yellow-poplar	8,956 (10)
White birch	10,310 (15)		

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[1] Italicized numbers in parentheses refer to literature cited at the end of this report. Scientific names of species are given only if they were reported by the source publication. Sampling techniques varied among sources, No endorsement of the data is intended; it is provided only for reference. Many experts agree that regardless of species, wood fuels have average higher heating values around 8,500 Btu/ovendry lb.

The dry weight basis is the ratio of the weight of water in wood to the ovendry weight of the wood. The formulas used in this paper require that moisture content be expressed on the wet weight basis.

Moisture content (MC) wet weight basis (WB) = MC_{WB}

$$= \text{(weight of water in wet fuel)/(total weight of wet fuel)}$$

$$= \frac{\text{(Weight of water in wet fuel)}}{\text{(Weight of wood, ovendry)} + \text{(Weight of water in wet fuel)}} \qquad (1)$$

Effect of Moisture Content

Moisture in wood or bark fuel evaporates and absorbs energy in combustion, Generally, all moisture escapes in stack gases as heated water vapor. Heat in water vapor escapes and is no longer recoverable as it exits the heat recovery system in stack gases. Generally, higher fuel moisture content or hotter stack gas temperatures result in more heat escaping in stack gases. The following formula (2) developed on the' basis of heat capacity and latent heat of vaporization of water, is used to estimate the quantity of heat which escapes in stack gases because of fuel moisture per pound of wet wood or bark fuel.

Stack gas heat loss caused by moisture (Btu/lb of wet fuel) =

$$MC_{WB} \cdot [970 + (212 - T_1) + (0.46 \cdot (T_2 - 212))] \qquad (2)$$

where

T_1 (°F) is the temperature of wood or bark fuel entering the furnace;

T_2 (°F) is temperature of stack gases beyond heat recovery devices; and

MC_{WB} is moisture content of the fuel on a wet weight basis expressed as a decimal fraction.

Effect of Hydrogen

Wood and bark generally contain about 6 percent hydrogen by dry weight. One pound of ovendried wood or bark contains about 0.06 pound of hydrogen. In combustion hydrogen combines with oxygen and forms water vapor. Water is by weight 1 part hydrogen and 8 parts oxygen. Therefore, 0.06 pound of hydrogen in combustion will form 0.54 pound of water. Heat in water vapor formed from hydrogen escapes from heat recovery systems via stack gases. The quantity of heat which escapes because of hydrogen-formed water vapor per pound of wet wood or bark fuel can be estimated using the following formula (3).

Stack gas heat loss caused by hydrogen (Btu/lb of wet fuel) =

$$0.54 \cdot (1 - MC_{WB}) \cdot [970 + (212 - T_1) + (0.46 \cdot (T_2 - 212))] \qquad (3)$$

where

MC_{WB}, T_1, and T_2 are the same terms as used in equation (2).

Dry Gas and Excess Air

Some heat escapes in dry (non-water vapor) gaseous products of combustion because the dry gases (mainly carbon dioxide) are at an elevated temperature when exiting the heat recovery system in stack gases. In addition, generally some excess air (in excess of theoretical air requirements for combustion) enters a furnace and exits along with stack gases, adding to the amount of heat which escapes in stack gases.

Ovendry wood or bark fuel generally contains approximately 50 percent carbon, 41 percent oxygen, 6 percent hydrogen, 1 percent nitrogen, and 2 percent "ash." Gaseous products of combustion include carbon dioxide and water that are formed when oxygen combines with carbon and hydrogen. The theoretical oxygen requirement for combustion of a pound of dry wood or bark fuel is about 1.40 pounds. Air is only 23.2 percent oxygen so that the oxygen requirement converts to a theoretical air requirement of 6.03 pounds. In addition to theoretical air, some excess air is always admitted to a furnace to sustain complete combustion. Excess air is commonly expressed as a percent of theoretical air, and referred to as percent excess air. The following formula (4) is used to estimate the quantity of heat that escapes in stack gases because of dry gas and excess air (based on the heat capacities of carbon dioxide nitrogen, and oxygen, and assuming complete combustion).

Stack gas heat loss caused by dry gas and excess air (Btu/lb of wet fuel) =

$$(T_2 - T_1) \cdot (1 - MC_{WB}) \cdot [(1.44 \cdot (\text{pct excess air})) + 1.56] \qquad (4)$$

where

T_1 (°F) is the temperature of air entering the furnace;

T_2 (°F) is stack gas temperature beyond heat recovery devices;

(pct excess air) is excess air expressed as a decimal fraction of theoretical air; and

MC_{WB} is moisture content wet weight basis.

Conventional Heat Loss

In addition to heat escaping in stack gases, other heat losses, referred to as conventional heat losses, are normally associated with combustion and heat recovery systems. Conventional heat losses include heat losses resulting from thermal radiation, conduction and convection of heat, incomplete combustion, and miscellaneous or unaccounted for heat losses. Heat losses from such factors are described as around 3 to 4 percent by Miller and Hansen (*14*) and Corder (*4*). However, 3 to 4 percent is somewhat arbitrary because escalation of heat losses can occur in some circumstances. Generally, as moisture in wood or bark fuel increases, combustion temperatures decline and furnace capacity decreases (e.g., less fuel can be burned in the furnace and still sustain combustion). In general, conventional heat losses tend to be more significant at reduced furnace capacity or with improperly sized or high moisture content fuel. It can be difficult or impossible to burn a particular fuel in a furnace that is not designed for the type of fuel being used.

A conventional heat loss factor of 3 to 4 percent, or less (in addition to heat escaping in stack gases) may be appropriate for a skillfully operated system burning the type of fuel for which the system was designed. However, the heat loss factor could be higher than 4 percent, especially with marginal quality fuel (fuel with excessive moisture or improperly sized particles), or with a combustion system which is not skillfully operated. Conventional heat loss per pound of wet fuel can be calculated by multiplying the heat loss factor times available potential heat (available potential heat is ovendry wood fraction times higher heating value, or (1 - MC_{WB}) • HHV, where MC_{WB} is wet weight basis moisture content, and HHV is higher heating value).

Calculating Recoverable Heat Energy

Recoverable heat energy per pound of wet fuel can be calculated after stack gas heat losses (caused by moisture, hydrogen, dry gas, and excess air) and conventional heat losses have been calculated. Recoverable heat energy is calculated as available potential heat minus estimated stack gas heat loss and conventional heat loss.

Recoverable heat energy per pound of wet fuel (Btu/lb) =

[(Higher heating value) • (1 - MC_{WB})]

- [(Stack gas heat loss per pound of wet fuel)

+ (Conventional heat loss per pound of wet fuel)] (5)

If recoverable heat energy is calculated to be less than zero, calculated recoverable heat energy becomes zero.

Generally, the maximum moisture content at which wood or bark can be burned in furnaces (without auxiliary fuel) is around 65 to 70 percent, wet weight basis. However, the range of fuel moisture content that is acceptable varies depending on design of the combustion system.

Figure 1 illustrates estimated heat losses and heat recovery for a wood fuel with typical conditions, at various moisture contents, as derived by using the formulas summarized in this paper. Recoverable heat is calculated with assumptions of successful and nearly complete combustion. With high fuel moisture content, poorly sized fuel, improper matching of furnace design and fuel type, or

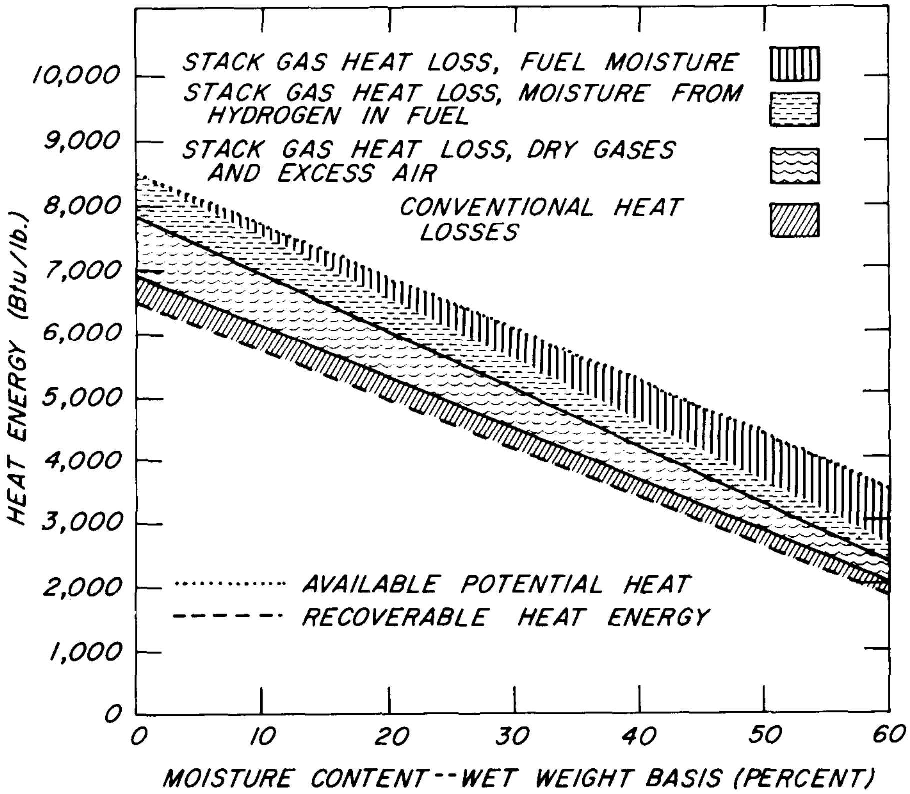

Figure 1.—Recoverable heat energy, available potential heat and heat losses for a typical wood fuel per pound of wet fuel at various moisture contents. The fuel has a higher heating value of 8,500 Btu per pound. The combustion heat recovery system is assumed to be operating with 40 percent excess air and a stack gas temperature of 500° F, fairly typical for an industrial system. A constant conventional heat loss factor of 4 percent and complete combustion are also assumed.

unskillful operation of equipment, it may be impossible to maintain combustion, and consequently recoverable heat energy would effectively become zero.

The effect of moisture content on recoverable heat energy is quite significant, and wood or bark fuels may contain considerable amounts of moisture. Evaluation of wood or bark as fuel should consider the effect of moisture on recoverable heat energy.

SUMMARY

The following information and formulas are needed to calculate recoverable heat energy in wood or bark fuel according to the procedure outlined in this paper.

Required Data

The higher heating value of the wood or bark fuel in average Btu per dry pound of fuel (HHV).

Temperature of air and fuel before entering furnace in degrees Fahrenheit (T_1).

Temperature of stack gases past heat recovery devices in degrees Fahrenheit (T_2).

Moisture content of the fuel, wet weight basis, as a decimal fraction (MC_{WB}).

Percent excess air, as a decimal fraction of theoretical (pct excess air).

Calculations[3]

Stack gas heat loss caused by moisture = $MC_{WB} \bullet [970 + (212 - T_1) + (0.46 \bullet (T_2 - 212))]$

Stack gas heat loss caused by hydrogen = $0.54 \bullet (1 - MC_{WB}) \bullet [970 + (212 - T_1) + (0.46 \bullet (T_2 - 212))]$

Stack gas heat loss caused by dry gas and excess air = $(T_2 - T_1) \bullet (1 - MC_{WB}) \bullet [(1.44 \bullet (\text{pct excess air})) + 1.56]$

Conventional heat losses (assuming 4 pct heat loss factor) = $0.04 \bullet \text{HHV} \bullet (1 - MC_{WB})$

Total heat loss = Sum of stack gas heat losses and conventional heat losses

Recoverable heat energy = $[(\text{HHV}) \bullet (1 - MC_{WB})] - (\text{Total heat loss})$

Some Useful Conversions

From	*To*	*Multiply by*
pound (lb)	kilogram (kg)	0.4536
kilogram	pound	2.2046
British thermal unit (Btu) (mean)	joule (J)	1055.87
joule	British thermal unit	0.0009471
Btu/lb	joule/ kg	2327.8
joule/ kg	Btu/lb	0.0004296

Temperature in degrees Fahrenheit = (1.8 • temperature in °C) - 32
Temperature in degrees Celsius = (temperature in °F - 32) ÷ 1.8

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[3] All results of calculations are interms of estimated Btu/lb of wet fuel at assumed moisture content.

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