RENEWABLE ENERGY ASSESSMENTS

AN ENERGY PLANNER'S MANUAL

by Marcia M. Gowen

with the assistance of Herbert A. Wade

Pacific Islands Development Program/
Resource Systems Institute

East-West Center
Honolulu, Hawaii USA 96848

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Marcia M. Gowen is a resource economist with the Pacific Islands Energy Project, a joint project of the Resource Systems Institute and the Pacific Islands Development Program at the East-West Center in Honolulu. She received her Ph.D. in agricultural economics from Ohio State University, Columbus, in 1983. She recently developed for the World Bank a handbook on household energy use in developing countries. Gowen's research focuses on energy economics, renewable energy assessment, and project analysis in developing countries.

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Printed in the United States of America.

Library of Congress Cataloging in Publication Data

Gowen, Marcia M., 1954–
Renewable energy assessments.

Bibliography: p.
Includes index.
1. Renewable energy sources–South Pacific Region–Econometric models. 2. Energy development–South Pacific Region–Planning. I. Wade, Herb. II. Title.
HD9502.S615G68 1985 333.79'099 85-10406
ISBN 0-86638-065-5

CONTENTS

List of Figures *vii*

List of Tables *ix*

Foreword *xi*

Preface and Acknowledgments *xiii*

List of Abbreviations, Acronyms, and Currency Conversions *xvii*

1. Introduction *1*
   - Energy in Development Planning *2*
   - Organization and Use of this Manual *3*
2. Energy Measurement: Definitions and Concepts *5*
   - Energy Assessment Components *5*
   - Fuel Resource Assessment *7*
   - Energy Technology Assessment *12*
   - End-Use Matching in Energy Planning *15*
   - Management of Renewable Energy Resources *16*
3. Financial and Economic Assessment *17*
   - Project Analysis: Questions to be Addressed *17*
   - Market Perspective *19*
   - Project Comparisons *21*
   - Project Time Horizon *21*
   - Valuing Benefits and Costs *23*
   - Type of Costing *31*
   - Decision Criteria *32*
   - Risk and Uncertainty in Renewable Energy Projects *34*
   - Project Analyses of Fuels and Technologies *35*

4. Energy Resource Assessments *37*
  Biomass Resource Assessment *38*
  Solar Resource Assessment *84*
  Hydro Resource Assessment *94*
  Wind Resource Assessment *106*
5. Energy Technology Assessments *117*
  Stoves *117*
  Charcoal Kilns *126*
  Biogas Digestors *131*
  Gasifier Systems *138*
  Solar Technology *148*
  Hydro Technology *163*
  Wind Technology *175*
  Electricity Pricing *187*
Appendices *195*
Bibliography *213*
Index *223*

LIST OF FIGURES

2.1 Energy transformation stages *6*
2.2 Input energy estimation *9*
2.3 Wood moisture content and LHVs *11*

4.1 Resource assessment steps *38*
4.2 Estimating stream flow with the float method *103*
4.3 Estimating stream flow with the weir method *104*

5.1 Typical household solar water heater *152*
5.2 Components of a small-scale hydro power system *165*
5.3 Power output and wind speed curves for two proposed wind machines *180*

LIST OF TABLES

3.1 Economic Tools for Project Analysis *19*

3.2 Appropriate Interest, Inflation, and Discount Rates to Use in Current Versus Real Discounted Cost Analyses *27*

3.3 A Comparison of Typical Benefits and Costs of Energy Projects in Financial Versus Economic Analyses *30*

4.1 Average Energy Content, Rotation Length, and Annual Yields for Selected Tree and Palm Species *48*

4.2 Average Energy Content and Production of Nonsustainable Forest Biomass and Residues *60*

4.3 Average Energy and Moisture Contents for Coconut Residues *62*

4.4 First-year Average Costs in a Financial Analysis for a Proposed Hawaiian Eucalyptus Tree Farm Excluding Power Generation *65*

4.5 Annual Average Costs in a Financial Analysis for a Proposed Hawaiian Eucalyptus Tree Farm Excluding Power Generation *65*

4.6 Economic Discounted Cash-Flow Analysis of a Proposed Hawaiian Eucalyptus Tree Farm with Power Generation Costs *66*

4.7 Average Energy Content and Production for Crops and Crop Residues in the Pacific *74*

4.8 Average Biogas Production *80*

4.9 Average Domestic Biogas Consumption *80*

4.10 Average Biomas Production from Various Waste Materials *81*

4.11 Monthly Average Daily Radiation for Yap *92*

4.12 Flow Conversion Table for Weir Method *105*

4.13 The Beaufort Wind Scale and Approximate Wind Speeds *111*

5.1 Estimated WBT or CCT Efficiencies of Stoves Used in Pacific/Asia Region *124*
5.2 Comparative Fuel Costs of Cooking with Electricity and Solid Fuels in Ponape *125*
5.3 A Break-even Analysis of Annual Average Costs for Charcoal Kilns in Kiribati *130*
5.4 Annual Average Costs and Benefits of a Palm Oil Sludge Biogas Plant in the Solomon Islands *138*
5.5 Energy Content and Uses of Fuel Gases *144*
5.6 Comparison of Experimental and Calculated High Heating Values when Gasifying Various Fuels *146*
5.7 Annual Average Costs and Benefits from a Gasifier Retrofit in the Cook Islands *149*
5.8 Annual Average Costs and Benefits of Solar Water Heating in Ponape, FSM *162*
5.9 A Financial and Economic Analysis of Annual Hydropower Costs for the Lehmasi River, Ponape, FSM *174*
5.10 Appropriate Power, Area, and Velocity Units and Constant Coefficients for Calculating Power Output from Wind Machines *177*
5.11 Wind Speed and Output Characteristics for Two Proposed Wind Machines in Aitutaki, Cook Islands *185*
5.12 Annual Energy Generated by Wind Generators and Resultant Diesel Fuel Savings *186*
5.13 Estimated Capital Costs of Two Proposed Wind Systems on Aitutaki, Cook Islands *187*
5.14 Annual Average Cost Estimation for a Proposed Wind-supplemented Diesel System Versus a Diesel System in the Cook Islands *188*
5.15 Marginal Annual Costs and Benefits from the Addition of a Wind Generator *189*
5.16 General Components in Electricity Production Costs *191*

FOREWORD

Renewable Energy Assessments: An Energy Planner's Manual is one of a series of technical tools prepared by the Pacific Islands Energy Studies Project of the Pacific Islands Development Program (PIDP) and the Resource Systems Institute (RSI) of the East-West Center. The energy project provides policy and planning assistance and technical support for energy development in the region.

The Energy Assessment Manual grew out of the perceived need to provide development and energy planners in the Pacific islands and Third World countries with a quick reference on the major elements requiring consideration in renewable energy planning. The manual is designed to facilitate first-cut, reconnaissance-level comparisons of energy alternatives and to suggest the general scope of future field investigations necessary to plan renewable energy projects. It is intended as a technical tool to supplement standard planning techniques. To be effectively utilized, it should be used in conjunction with more detailed guides to socioeconomic and engineering planning.

It is the hope of PIDP that this energy planner's guide will assist government officials in planning technically sound and economically viable projects. It is our belief that it is only through such planning that developing countries can reduce the cost of energy to their people.

Filipe N. Bole
Director
Pacific Islands Development Program

PREFACE AND ACKNOWLEDGMENTS

In practice, energy assessment is as much an art as a science. After coming to know typical, average values for energy statistics, over time the energy analyst develops a feel if the situation–fuel, technology, and culture–differs significantly from the average to discard such averages or to question the reliability of field data. More often, an energy planner will need to rely on common sense and intuition when deriving reasonable estimates of a country's renewable energy supply. The importance of deriving reasonable resource supply estimates cannot be overemphasized, however, since energy strategies and decision making revolve around such numbers.

Estimating renewable energy potential is particularly difficult. Governments and private users will need to weigh carefully the advantage of using an abundant resource such as renewables in the tropics with the greater risk involved in producing or using new, sometimes unproven, fuels and technologies. Unlike fossil fuels, renewable resource use is extremely site-specific. Conducting careful, realistic energy assessments is the first step toward responsible decision making. This manual will serve as a road map, hopefully, for energy planners in the Pacific region. I acknowledge, though, that maps often have some inaccuracies or gaps that can only be filled by those who live in the area. This is the real job of the country's energy planner–to know the map. I have merely located guideposts.

As with all major efforts, this book has benefited from the valuable input and support of many colleagues whose knowledge of energy and the Pacific islands has greatly enriched the manual. For his initial encouragement, continued input based on country experience, and critical review, Mr. Sam Pintz, leader of the Pacific Islands Energy Project, deserves special recognition. For his thorough review and written contributions to this manual on the solar, hydro, and wind energy sections, Mr. Herbert A. Wade of the United Nations Pacific Energy Development Project in Fiji receives particular thanks.

Institutional support has been critical to the book's development. For this, I am indebted to Mr. Filipe Bole, director of the Pacific Islands Development Program, Dr. Michael Hamnett, PIDP research director, and Dr. Seiji Naya, director of the Resource Systems Institute, for their institutional support. Mr. William Paupe, director of the South Pacific Regional Office of the U.S. Agency for International Development, has been instrumental in securing financial support for the Pacific Islands Energy Project.

Within the East-West Center, many colleagues contributed expertise in specific areas. Dr. Kirk Smith gave useful technical comments on the working draft, Dr. Deepak Bajracharya provided input on the biogas sections, fellow economists Dr. John Dixon and Dr. Fred Hitzhusen made helpful comments on the project analysis chapter, and Mr. Napoleon Vergara provided species names and preferred uses on the forestry section. For their review and enlightening input, I also wish to thank Mr. James Rizer, Mr. Charles Feinstein, and Mrs. Cynthia Lowry.

I would be remiss not to mention the colleagues from regional institutions who also gave comments on the manual. Dr. Tony Weir of the South Pacific Bureau of Economic Cooperation was particularly helpful with a thorough review of the manuscript. Dr. Ken Newcombe of the World Bank had significant indirect and direct input into the manual through his position as the primary researcher for the Pacific Islands Energy Mission Reports (1982), from which many examples in this manual have been drawn, and from my work with him while at the World Bank. Mr. Wilem Floor and Dr. Anwar Malik, also with the Energy Department at the World Bank, provided helpful information to me.

A manuscript cannot be produced without significant effort and time spent in preparation. Titilia Barbour has been instrumental in typing the varied drafts of this document. And for their patient assistance—at times across many miles and different institutes—Sheryl Bryson and Tina Clark, my editors, receive particular recognition for their superb job in keeping me straight. Lois Bender certainly did more than was required with the typesetting, despite last-minute changes and revisions. We all appreciate her patience. As always, the responsibility for any remaining errors rests with me.

Finally, for their continuing support through the years, I dedicate this book to my parents and family.

It is my hope that this manual will serve as a catalyst for better understanding of and decision making for renewable resources for energy planners in the Pacific islands and other countries.

Marcia M. Gowen

LIST OF ABBREVIATIONS, ACRONYMS, AND CURRENCY CONVERSIONS

Abbreviations

AC	alternating current
ad	air dried (moisture content)
B/C	benefit-cost ratio
$\bar{C}$	monthly cloud cover
CH_4	methane
CO_2	carbon dioxide
C_{op}	overall power coefficient
CCT	controlled cooking test
DC	direct current
DH	direct heat
DS	diesel system
E_A	annual energy
EFF_{sys}	gross efficiency of a system
ei	efficiency index
E_K	kinetic energy
FV	future value
$\bar{H}$	horizontal surface radiation
$\bar{H}_c$	clear day radiation
$\bar{H}_o$	extraterrestrial radiation
hr	hour
IRR	internal rate of return
KPT	kitchen performance test
K_T	clearness index
mcdb	moisture content dry basis
mcwb	moisture content wet basis
$\bar{n}/\bar{N}$	average fraction of possible sunshine hours
NPV	net present value
od	oven dried (moisture content)
O+M	operation and maintenance
POME	palm oil mill effluent
P_{max}	maximum power
PPS	percent of possible sunshine
P_w	wind power
sec	second
SP	shaft power
V	wind speed (velocity)
V_{ave}	average velocity of stream
V_c	cut-in wind speed
V_f	furling or cut-out wind speed
V_r	rated wind speed
V_s	surface velocity of stream
WBT	water boiling test
W_p	peak watts
WSS	wind-supplemented system
Σ	summation
ρ	density of air

Note: Abbreviations for units are defined in Appendix A.

Acronyms

A	Australia
EMR	Energy Mission Reports
EPRI	Electric Power Research Institute
ESCAP	Economic and Social Commission for Asia and the Pacific
EWC	East-West Center
FAO	Food and Agriculture Organization of the United Nations
FSM	Federated States of Micronesia
HNEI	Hawaii Natural Energy Institute
NZ	New Zealand
PIDP	Pacific Islands Development Program
PNG	Papua New Guinea
RSI	Resource Systems Institute
SERI	Solar Energy Research Institute
SI	Solomon Islands
SPEC	South Pacific Bureau of Economic Cooperation
TPI	Tropical Products Institute
UN	United Nations
UNDP	United Nations Development Programme
US	United States

Currency Conversions

Australia	A$1.00 = US$1.14
Fiji	F$1.00 = US$1.16
New Zealand	NZ$1.00 = US$0.85
Solomon Islands	SI$1.00 = US$1.16

Note: Average 1981.

1

INTRODUCTION

Renewable resources such as coconut shells, wood, and crop residues have always been used in the Pacific region for energy production, mostly as low-quality domestic fuels. With rising or fluctuating petroleum prices and improved conversion technologies, under certain conditions these renewable resources may now provide high-quality energy through electricity or steam heat while also being competitive with petroleum fuels. Given the large renewable energy potential identified by the Energy Mission Reports (1982)* for nine Pacific island countries, the feasibility of renewable fuels is being seriously considered by energy planners in the region. To estimate the region's renewable energy potential, consistent assessment methods and data are needed.

This manual brings together energy assessments, data descriptions, and economic analyses needed by the energy planner. First, it provides energy analysts with a common set of equations for comparing fuels and conversion technologies to make general but not necessarily definitive energy supply and economic feasibility assessments. Second, the manual gives planners empirical data on fuels and energy technologies used in tropical regions, particularly in the Asia-Pacific region. Since most biomass research has been conducted in temperate zones, energy assessments for the tropics are often limited by the lack of data. Estimating tropical energy resources requires data on tropical yields, production rates, and ecological constraints. This manual brings these data together from various energy studies for comparison by the energy planner. The manual also presents analysts with simple economic tools to make financial analyses of alternative energy systems. The presentation gives the basic benefits and costs that are needed for a cursory financial analysis of a system.

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* The Energy Mission Reports were produced and published through the collaborative efforts of the South Pacific Bureau of Economic Co-operation, the Australian National University, the Pacific Islands Development Program of the East-West Center, the Economic and Social Commission for Asia and the Pacific, the European Economic Community, and the United Nations Development Programme.

ENERGY IN DEVELOPMENT PLANNING

Good energy planning is critical to development. Energy is needed for economic growth, so fuels are important, especially to oil-importing nations. In most developing countries, governments and large multinational investors shape energy policy planning by initiating research and discovering, developing, or importing energy sources. For developing countries with large petroleum import bills and limited national budgets, fuels grown or developed locally can be attractive substitutes to imported fossil fuels if the locally produced fuels are economically feasible and socially acceptable. Potential foreign exchange savings, use of local labor, and increased economic integration generated from indigenous energy projects are quite attractive outcomes to a government. A realistic energy policy based upon good planning can help a country adjust to changes in its energy mix.

A first step toward energy planning is assessing the resource supply and technology feasibility. The potential supply of indigenous energy resources needs to be estimated to see if indigenous fuels can replace imported fuels. A technological assessment is needed to determine the probable success or failure of different conversion technologies (e.g., digestor, diesel generator, wood boiler, or wood gasifier). Following these assessments, a fuel end-use profile is needed to match end needs with the appropriate fuels and technologies.

A major problem in past energy planning has been a lack of data. Too often, gross fuel estimates of "potential supply" severely mislead decision makers regarding the *actual* potential of the fuel or the technology. Consequently, these poor estimates may lead toward energy policies that result in high operation and maintenance costs, displacement of agricultural lands, and harmful environmental and social effects. It is critical to energy analysts that the best possible energy assessment estimates and economic analyses are made, subject to budget and time constraints. The methods given in the manual will help planners calculate better estimates.

ORGANIZATION AND USE OF THIS MANUAL

The manual has two main sections: (1) a background on energy and economic definitions, concepts, and methods used in making energy assessments (Chapters 2 and 3), and (2) the fuel and technology assessments (Chapters 4 and 5). Chapter 2 presents general energy definitions and concepts needed for calculating energy estimates. Economic definitions and formulas used in later chapters (4 and 5) are given in Chapter 3. Chapter 4, on fuel assessment, gives equations and data for energy planners to calculate their available resource base and its energy potential. Chapter 5, on technology assessment, shows a planner how to estimate the usable energy that could be produced by a technology. Formulas are given within the assessment chapters for calculating the resource and energy potential of a fuel or technology. Empirical estimates of conversion factors for specific fuels and technologies are also given in those chapters.*

This manual is written for energy technicians and planners. It is to be used to calculate *preliminary* energy resource and technology assessments as well as to do *rough* financial analyses. Wherever possible, tropical data have been provided for use in the fuel and technology assessment equations. If regional data do not exist for a particular fuel or technology, data from other countries generally are not substituted. This "omission" is to encourage planners to develop their own databases using existing in-country data sources (e.g., local extension agents, farmers, and energy agencies). It is hoped that better estimates, as well as broader databases, will be encouraged and developed because of this manual.

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* The calculations and data presented in this manual often are adapted from the Energy Mission Reports (1982).

2

ENERGY MEASUREMENT: DEFINITIONS AND CONCEPTS

To estimate the actual energy available to accomplish a task, the potential energy from the fuel source and the actual energy delivered from an energy-converting technology must be known. This chapter provides definitions of common terms and the basic concepts involved in making an energy assessment of a fuel or energy conversion technology.

ENERGY ASSESSMENT COMPONENTS

Two steps occur in an energy assessment:

1. **Resource fuel assessment**—measuring the potential input energy from a fuel before it is used in a conversion technology; and
2. **Energy technology assessment**—measuring the usable energy delivered by an energy technology after fuel conversion.

In each step, factors important for making realistic estimates change according to the type of fuel and conversion technology used. In step 1, the fuel (or energy) resource supply assessment, the **potential input energy** in a fuel is calculated, where input energy is defined as the energy potential in a fuel before it is burned or converted to energy in a technology. Resources discussed in this manual include those from forests, agriculture, animal and solid wastes, solar, water, and wind. In step 2, the potential input energy in the fuel is converted by a technology into **usable energy**, where usable energy is the actual amount of energy given off or provided from the technology. Figure 2.1 illustrates how these two steps are made in converting a fuel source to

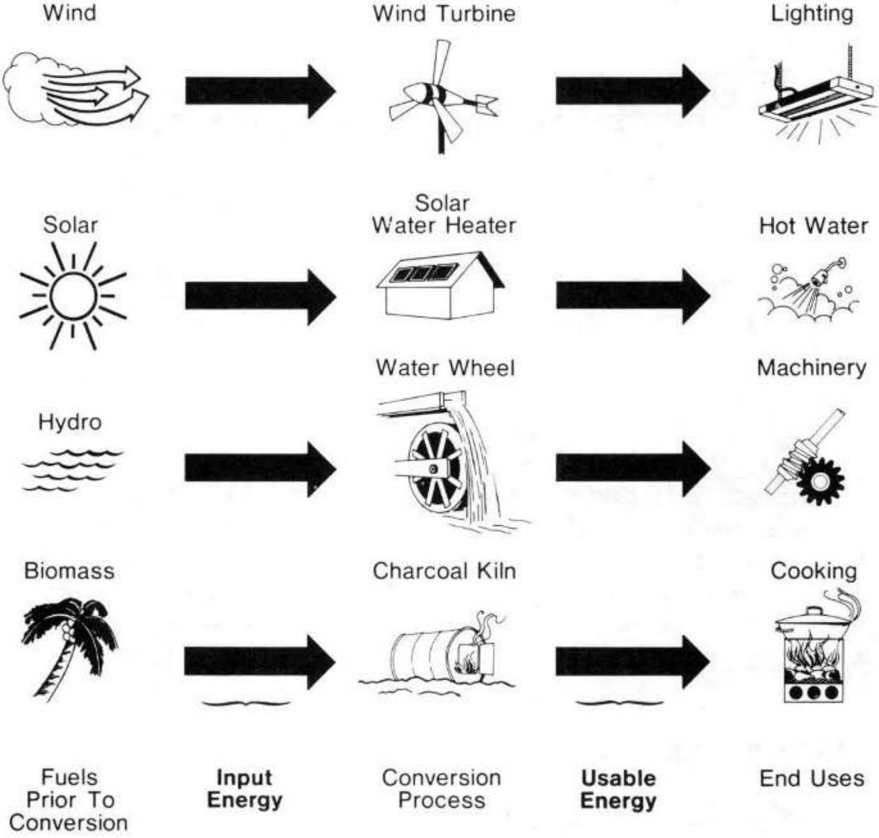

Wind
Wind Turbine
Lighting
Solar
Solar Water Heater
Hot Water
Hydro
Water Wheel
Machinery
Biomass
Charcoal Kiln
Cooking
Fuels Prior To Conversion
Input Energy
Conversion Process
Usable Energy
End Uses

Figure 2.1. Energy transformation stages.

energy. Some technologies described in this manual are stoves, biogas digestors, gasifiers, solar systems, wind machines, and mini-hydro systems.

Chapters 4 and 5 give equations for making fuel assessments (step 1) and energy technology assessments (step 2), respectively. General energy units, principles, and definitions that apply to all fuels and technologies are discussed in this chapter, with examples taken from later chapters.

Energy Measurement Units

Confusion often exists about energy terms due to their various units and systems of measurement. Two basic systems of measurement are used—the International System of Units (SI) and the British system (Appendix A). Unfortunately for the energy planner, both systems are used in the Pacific region, often making energy studies difficult to compare without the appropriate conversion factors. Common energy units and conversion factors used in both systems, as well as a glossary of symbols, are presented in Appendix A. Materials in this appendix are critical to making energy assessments and will be used for all conversion factors presented in later chapters. Manual users should refer to it now to become familiar with the energy units and symbols used in the text.

Energy Versus Power

It is important for energy planners to clarify the difference between energy and power. **Energy** refers to the ability to do work or provide heat. It is expressed in kilowatt hours (kWh) or joules (J) in the SI system and British thermal units (BTUs) in the British system. The energy produced from a fuel after conversion by an energy technology is usually reported as megajoules (MJ) or million BTUs (MMBTUs). These energy units and their conversion factors are given in Appendix A. Energy is expressed as*

$$\begin{array}{lllll} \text{Energy} & = \text{Power} & \times & \text{Time} & \qquad (2.1) \\ \text{(MJ)} & \text{(kW)} & & \text{(sec)} & \\ \text{(BTU)} & \text{(BTU/hr)} & & \text{(hr)} & \end{array}$$

Power is a unit of energy per unit of time. It is measured in kilowatts (kW) or referred to as joules per second (J/sec) or BTUs per hour (BTU/hr). Power is important with electricity production. For instance, peak watts (W_p) refer to the maximum power given off by a battery or energy technology at a given point in time. Power is expressed as

$$\begin{array}{lllll} \text{Power} & = \text{Energy} & \div & \text{Time} & \qquad (2.2) \\ \text{(kW)} & \text{(MJ)} & & \text{(sec)} & \\ \text{(BTU/hr)} & \text{(BTU)} & & \text{(hr)} & \end{array}$$

FUEL RESOURCE ASSESSMENT

A critical step in an energy assessment is preparation of realistic input energy estimates for the potential fuel supply. Chapter 4 gives equations for calculating potential input energy from various renewable fuels. The basic definitions used in the equations are given in this chapter.

---

* Units are given for the International System of Units and British systems, with British units reported below SI units.

In step 1, the input energy potential of a fuel is measured. This energy is defined as the energy potentially available from a fuel before the fuel goes into a conversion technology. Many factors, such as moisture content or specific gravity, affect the input energy estimates. Of primary importance for the energy analyst is to know the correct energy value (or heat content) of a fuel before it is burned, fermented, or gasified.

For biomass resources, the *moisture content* of a fuel is the critical factor affecting the input energy value. Water moisture affects the energy potential of a fuel because it must be evaporated before the fuel's organic material provides usable heat. A higher moisture content of a fuel thus lowers the potential input energy from the fuel.

Three types of heat losses occur due to the water in a fuel: (1) heat loss due to warming up the "natural" water molecules in a biomass fuel to the evaporation state; (2) heat loss due to vaporizing this warmed water; and (3) heat loss due to water molecules formed during combustion from atmospheric oxygen and hydrogen molecules in the fuel. Appendix B provides a detailed discussion on moisture content.

As shown in Figure 2.2, the common energy definitions that adjust for a fuel's moisture content are **high heat values** (HHV) and **low heat values** (LHV), with the following definitions:

High Heat Value (HHV)—the oven-dry or *calorific* heat value of a fuel (i.e., energy losses due to fuel moisture are added into this value), sometimes referred to as gross heat value.

Low Heat Value (LHV)—the energy content of a fuel after the heat of vaporization is deducted, commonly referred to as the net heat value.

The difference between high and low heat values for a fuel is the inclusion or exclusion, respectively, of the energy needed to evaporate a fuel's water content. A simple formula (Tillman 1978) for calculating the LHV from the HHV is

$$\text{LHV} = \text{HHV} - 0.0114\,(\text{HHV})\,(\text{MC})$$

$$\text{thus, HHV} = \frac{\text{LHV}}{1 - 0.0114\,(\text{MC})} \qquad (2.3)$$

where MC is the moisture content of fuel and 0.0114 is an adjustment coefficient. If the wet and oven-dry weights of a fuel are known, the moisture content of a fuel can be found using the following formula:

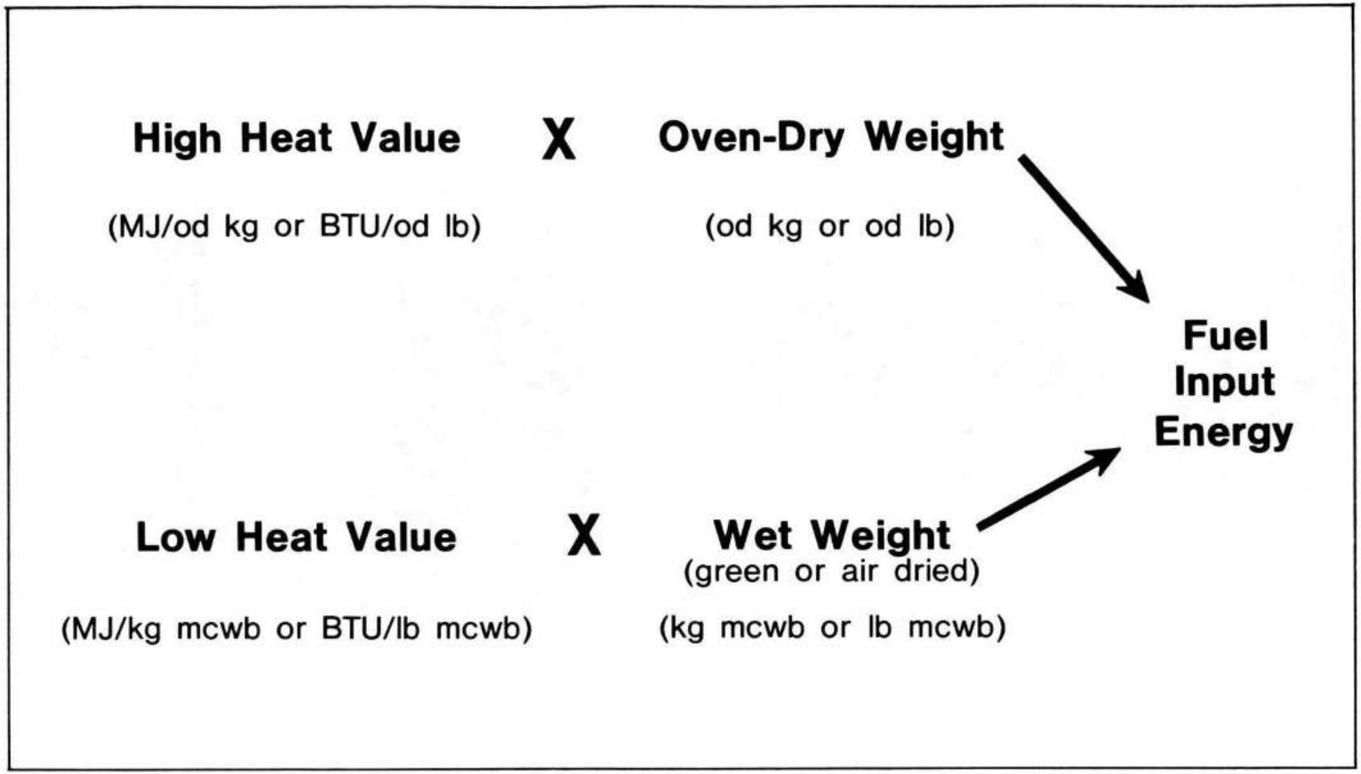

High Heat Value
X
Oven-Dry Weight
(MJ/od kg or BTU/od lb)
(od kg or od lb)
Fuel
Input
Energy
Low Heat Value
X
Wet Weight
(green or air dried)
(MJ/kg mcwb or BTU/lb mcwb)
(kg mcwb or lb mcwb)

Figure 2.2. Input energy estimations.

$$\text{Moisture Content Wet Basis (mcwb)} = \frac{\text{Wet Weight} - \text{Oven-dried Weight}}{\text{Wet Weight}} \times 100\% \qquad (2.4)$$

Every LHV for a fuel should be followed by the fuel's specific moisture content for *that* value. Unless a biomass fuel is reported in **oven-dry** (od) weight, it has some moisture; its moisture content wet basis (mcwb) should be given.* **Air-dried** (ad) heat value is another common energy term that refers to the atmospheric equilibrium moisture content of a fuel when the fuel is left outside over time. The **green** weight refers to the moisture content of wood directly after it has been cut before moisture has evaporated to air-dried or oven-dry weight.

For fuel energy assessments to be accurate, the heat value (od, ad, or green) must correspond to the actual moisture conditions of the renewable fuel before it is burned. For example, oven-dry weights and HHVs are often given for biomass fuels even though oven-dry conditions never exist for fuels that are burned in the field or in households. In tropical areas, such as in the Pacific islands, moisture contents of wood resources can range from 20–30 percent mcwb air-dry to 40–60 percent mcwb green basis. Figure 2.3 shows how the LHV rapidly decreases as a fuel's moisture content increases.

From formulas 2.3 and 2.4, oven-dried weight and HHVs can always be determined if wet (or air-dried) weights and their moisture content are known. Conversely, if oven-dried weights for HHVs are known along with an expected moisture content, the wet or air-dried weights can be calculated. The following example shows how to calculate input energy for coconut shells if the wet weight and HHV are known.

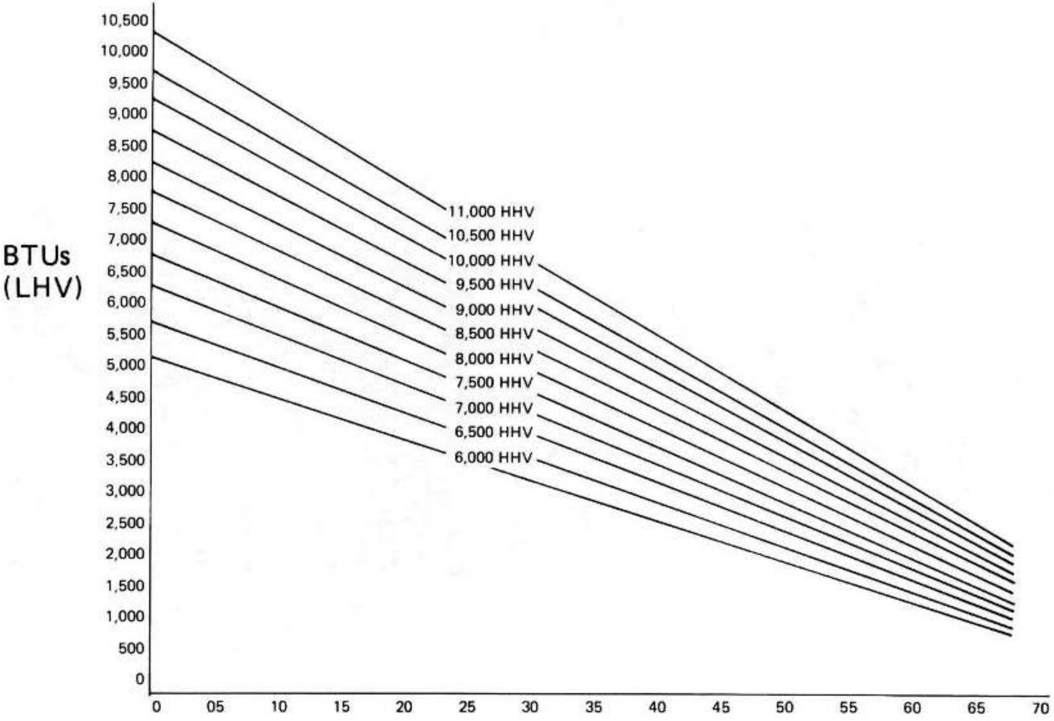
Example:

An owner of a copra plantation wants to know the potential input energy of the unused coconut shells. Plantation yields are 400 metric tons (MT) of dry copra per year. We know that about 0.9 kilograms (kg) of wet coconut shells, at 40 percent mcwb, are produced as a by-product for every 1 kg of dry copra produced (Energy Mission Reports 1982). Thus, the annual total is

$$\begin{aligned}\text{Annual Wet Weight} &= (0.9 \text{ kg mcwb shells/kg dry copra})\ (400{,}000 \text{ kg mcwb shells/yr})\\ &= 360{,}000 \text{ kg mcwb shells/yr}\end{aligned}$$

---

* The two bases for calculating moisture content are described in Appendix B. Moisture content wet basis will be used for calculations in this manual.



% Moisture Content (wet basis)

Figure 2.3. Wood moisture content and LHVs (Source: Lamb-Cargate 1984).

If we assume that coconut shells have an HHV of 20.85 MJ/od kg (Energy Mission Reports 1982), then the wet shell has an LHV of

LHV = 20.85 MJ/od kg − (0.0114) (20.85 MJ/od kg) (40)
= 11.3 MJ/kg mcwb shells

Using this LHV, the annual input energy potential from wet waste coconut shells on the copra plantation is

Annual Input Energy = (360,000 kg mcwb shells/yr) (11.3 MJ/kg mcwb)
= 4,068,000 MJ/yr
= 4.07 TJ/yr

ENERGY TECHNOLOGY ASSESSMENT

Step 2 in an energy assessment estimates the actual amount of energy delivered by a technology (the usable energy) after conversion. Input energy values consider only the fuel's potential energy characteristics. The amount of heat or work actually delivered for use (e.g., mechanical, electrical, or steam heat) from a technology is affected by the heat loss characteristics, or the gross conversion efficiency, of the energy technology that processes the fuel. For instance, when fuelwood is burned in a wood stove, heat losses occur because the stove is not totally efficient. Since no energy conversion process is 100 percent efficient in transforming a fuel's input energy potential into usable (delivered) energy, every energy assessment of a technology needs to adjust for that technology's conversion efficiency. The importance of such conversion efficiencies will be discussed further in Chapter 5, on technology assessment.

Estimating Usable Energy

In order to estimate the usable energy produced by an energy technology, it is helpful to know that two energy laws, commonly referred to as the First and Second Laws of Thermodynamics, influence the amount and quality of energy produced by the technology. The First Law of Thermodynamics, also referred to as the Law of Conservation of Energy, states that energy can be neither destroyed nor created, rather it is conserved. This law simply says a balance of energy always exists so that total energy inputs equal total dissipated and delivered energy outputs. That is, although the forms of energy may change (e.g., fuelwood energy potential becomes mechanical steam energy plus wasted heat), the total energy balance of the "before and after" systems is equal. The first law is used in energy calculations of energy balances.

While all energy is conserved in different forms, only some of these forms are useful or usable energy. The conversion efficiency needed to calculate the usable heat from a technology is referred to as the **gross energy efficiency**. It equals the actual amount of heat delivered or produced (usable energy) divided by the amount of heat received (input energy) (Krenz 1976). This efficiency can be written as

$$\text{Gross Efficiency} = \frac{\text{Energy Actually Delivered by Technology}}{\text{Fuel's Input Energy}} \times 100\% = \frac{\text{Usable Energy from Technology}}{\text{Fuel's Input Energy}} \times 100\% \tag{2.5}$$

Example:

In a wood gasifier, 10 MJ of heat actually was delivered by the fuel source, coconut wood, although 17 MJ of input heat potential was available. The gross efficiency is

$$\text{Gross Conversion Efficiency of Coconut Wood in Gasifier} = \frac{10\ \text{MJ}}{17\ \text{MJ}} \times 100\% = 60\%$$

The Second Law of Thermodynamics states that it is impossible "to convert heat to work with no effects" (Krenz 1976). In practice, the second law means no conversion of a fuel into heat or work is totally efficient; some loss occurs during energy conversion. Besides the gross efficiency, there is also the **net efficiency**, which represents the quality of the energy conversion. It is the theoretical minimum amount of usable energy needed to perform a function divided by the actual amount of usable energy used to perform the function (usable energy). The relationship is written as

$$\text{Net Efficiency} = \frac{\text{Minimum Energy Needed}}{\text{Energy Actually Used}} = \frac{\text{Theoretical Minimum}}{\text{Usable Energy}} \tag{2.6}$$

Example:

Using the same wood gasifier as in the previous example, suppose the theoretical minimum heat needed is only 8 MJ for the 10 MJ of delivered heat actually used. Thus, the net efficiency is

$$\text{Net Efficiency} = \frac{8\ \text{MJ}}{10\ \text{MJ}} \times 100\% = 80\%$$

This second law efficiency shows by how much the conversion process achieves or fails to achieve its best attainable efficiency (Erlich et al. 1977). That is, the gross efficiency tells how well the technology actually performs, but the net efficiency tells if it could do any better. The gross efficiency, thus, is a realistic performance measure. Improvement margins for a technology are given by the net efficiency.

It is important to adjust for gross conversion efficiencies, because they affect the amount of fuel (supply) actually needed to meet a given energy demand. For example, the energy requirement for an industrial or domestic user is often known, so a technology is sized to produce that level of demand. The demand is the usable (output) energy needed. The amount of feedstock needed to produce that level of usable energy therefore must be adjusted by the technology's conversion efficiency for that fuel to get the input energy of fuel necessary to run the system. Without adjusting for conversion efficiencies of a technology, the actual fuel requirement may be seriously underestimated.

When using the gross efficiencies given later in this manual, it must be remembered that conversion efficiencies are highly fuel and condition specific. For instance, the combustion efficiency for any technology will depend on the system's design, operation and maintenance record, utilization level of the system (under vs. full capacity), as well as the moisture content of a fuel. Conversion efficiencies reported for technologies often reflect laboratory conditions where well-designed, well-maintained systems exist. The conversion factors reported in the technology assessment chapter (Chapter 5) thus are representative averages with a wide variation for field conditions.

Determining Energy Supply Needs from Energy Demand

An energy analyst often will be faced with the necessity to work backward, that is, he or she will know the energy demand of a village or industry but will need to determine the energy supply that could meet the demand. The following example shows how to combine information given in steps 1 and 2 to determine input energy needs on a wet basis (mcwb) or an oven-dry basis from energy demand.

Example:

If the conversion efficiency of coconut in a wood gasifier system is 60 percent and the usable energy requirement (demand) of the plantation owner is 10 MJ, then the input energy requirement is

Input Heat Needed	=	10 MJ Usable Heat Needed	÷	0.60 Gross Conversion Efficiency of Gasifier	=	17 MJ (16,100 BTU)

where 1 MJ = 948 BTU

If oven-dry coconut wood used in the gasifier has an average HHV of 19 MJ/od kg, then 0.89 kg of oven-dry wood is needed per hour.

Amount Oven-dried Coconut Wood Needed	=	17 MJ Input Energy Needed	÷	19 MJ/od kg od HHV	=	0.89 od kg

If air-dried coconut wood is used (as is normally the case), and it has an equilibrium air-dried moisture content of about 30 percent mcwb, then its low heating value is

$$\begin{aligned} \text{LHV} &= \text{HHV} - 0.0114\ (\text{HHV})\ (\text{MC}) \\ &= 19\ \text{MJ/od kg} - 0.0114\ (19\ \text{MJ/od kg})\ (30) \\ &= 12.5\ \text{MJ/kg mcwb} \end{aligned}$$

Thus, the air-dry weight needed to provide 17 MJ of input energy is

Amount Air-dried Coconut Wood Needed	=	17 MJ Input Energy Needed	÷	12.5 MJ/kg mcwb Energy Content	=	1.36 kg mcwb

As shown by this example, the supply estimates (amount of wood needed) are greatly influenced by the use of oven-dry or air-dried units. Both estimates are correct, but to have meaning to energy analysts, each set of estimates must have the moisture content of the wood specified.

END-USE MATCHING IN ENERGY PLANNING

While it is helpful to improve a technology's net or gross efficiency, a more critical issue for an energy planner is the appropriateness of the fuel or technology for a particular end use. End-use matching deals with optimum resource use, linking a fuel's energy quality with the socioeconomic effects involved in obtaining and producing energy from the fuel.* A planner should consider resource supply and environmental constraints, political feasibility, and practical adoption as affecting end-use matching. In practical terms, end-use matching implies that a high-quality, expensive fuel such as electricity may not be appropriate for providing rural cooking or residential heating but should be saved for lighting and industrial energy consumption while alternative technologies, such as stoves using low-quality heat sources (wood, charcoal, or biogas), may be a better use of a country's resources for rural cooking.

MANAGEMENT OF RENEWABLE ENERGY RESOURCES

A major attraction of many indigenous nonfossil energy resources such as biomass, wind, solar, and water is that their supply is potentially unlimited over time. These infinite supplies, however, depend upon proper resource management. For instance, the regenerative rates of biomass fuels such as forests and crops can be exceeded through overharvesting; water resources used to produce hydroelectric power require proper watershed and soil conservation practices; and wind and solar resources need adequate space and operating conditions for maximum energy production. Thus, proper management policies are needed to ensure long-term supplies of renewable resources. Government agencies may need to enforce such management practices through the use of government incentives or restrictions for private and public resource owners. These sustainability characteristics are important factors to include in the fuel assessment equations (see Chapter 4). Serious attention should be given by energy planners to such environmental constraints, and these constraints need to be used in calculating actual (realistic) renewable energy supplies.

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* End-use matching is used in a broader sense than thermodynamic matching, which generally matches the quality of energy produced by a fuel with the end use that could utilize that quality. For instance, low-quality uses such as cooking should be matched with low-quality energy fuels such as wood but not electricity, which is a high-quality energy form. End-use matching is a broader concept that includes matching a fuel's optimum social, environmental, economic, and energy quality characteristics to the end use.

3

FINANCIAL AND ECONOMIC ASSESSMENT

Determining the financial or economic feasibility of a fuel production or conversion technology is an important part of energy planning. Private individuals or communities will generally not produce a fuel or adopt a technology if positive financial benefits do not exist. Likewise, society needs to have positive economic benefits before adopting a proposed project. This chapter outlines and defines simple tools that can be used in making project analyses from a private (financial) and a social (economic) perspective. Such tools are used later in the fuel and technology assessment chapters.

PROJECT ANALYSIS: QUESTIONS TO BE ADDRESSED

Project analysis helps development planners assess a project's merits. The assumption is that good projects improve social welfare and encourage economic growth. Conversely, poorly designed and executed projects may damage social well-being and inhibit economic growth.

Project analysis provides planners with economic information (benefits and costs) that can be used by decision makers and communities when deciding to adopt or reject a project. It estimates the flows of economic benefits and costs to particular groups in society. This economic information also can be used to help determine priorities for rationing development funds. While financial or economic project analysis data needs are great, requiring monetary values on all benefits and costs of a project, it is the most common development planning tool used to assess a project's economic worth.

The first step in project analysis is to define the project goal. In the beginning of any energy project or planning strategy, the social goal or purpose needs to be made clear. In energy planning or assessment, the project's original goal may be to provide inexpensive fuels for residents and industries, but it may change in later years. For example, as imported petroleum becomes more expensive, policy objectives may change to encourage conservation by raising petroleum-derived energy prices (electricity) or to find cheaper local fuels.

A variety of economic tools are used in project analysis for assessing the economics of the project. These methods and definitions, available to any energy planner, address different economic aspects of an analysis. This section identifies the important questions a planner should ask and discusses the types of economic methods that could be used to answer each question. Any project analysis uses a combination of these methods, but all analyses must include answers to each question. The six questions important to project analysis and the suggested order for addressing them are

1. What is the perspective used when valuing benefits and costs?
2. What type of project comparisons are used?
3. What is the time horizon used in reporting benefits and costs?
4. How are benefits and costs valued?
5. What type of costing concerns the analyst?
6. What criteria are used in deciding to reject or accept a project?

The economic tools or methods of analysis associated with these questions (Table 3.1) are not mutually exclusive. For example, both a first-year marginal cost analysis and a first-year average cost analysis could be made for a project. Generally, the first issue to address in any project analysis is identification of the analytical perspective. Either financial (private market) or economic (social) cost analyses are made in economic assessments. Social accounting and environmental impact assessments are two other types of noneconomic project analyses that are important but not discussed in the manual. Choosing the market perspective helps define the project's target group as either private individuals or society in general. After identifying the market perspective, the types of project comparisons required must be decided. We must initially define the project boundaries to avoid problems later in the assessment. The project's time horizon must also be clearly defined at the outset.

After deciding the market perspective, type of comparison, and time horizon, a planner can make decisions about what to include in project benefits or costs (i.e., the valuation measure) and types of

Table 3.1. Economic Tools for Project Analysis

Market Perspective	Project Comparisons	Time Horizon	Valuation Measures	Type of Costing	Decision Criteria
financial	before/after	first-year	private cash	average	break-even
economic	with/without	annual	social values (shadow-prices)	marginal	net benefits (benefits − costs)
social accounts		cash flows	in-kind values		net present value
environmental impacts			weights		incremental net benefits
					benefit/cost ratio
					simple payback
					discounted payback
					internal rate of return
					cost effectiveness

costs (i.e., average or marginal). For example, private market prices are always used in a financial analysis, whereas social values are used in economic analyses. Finally, after identifying the type of project and methods of benefit or cost valuation, the project's benefits and costs must be compared. Decision criteria are formulas that compare benefit and cost streams, with different criteria showing somewhat different financial or economic attributes of a project.

MARKET PERSPECTIVE

An analysis can take different perspectives on what to include as important measures of a project's impacts. These perspectives differ according to the target group, such as a private firm, a region, or a country. Four perspectives are commonly used. These are financial analysis, economic analysis, social accounts, and environmental impact statements.

A **financial analysis** uses only a private market perspective for valuing benefits and costs. Private market values represent current or real (current prices minus inflation) prices as they are incurred by an investing unit (e.g., individual, household, or community) in the private sector. This type of analysis is what we as individuals carry out when deciding to adopt or reject a project.

An **economic analysis** recognizes that the private market may not be able to or fails to value the full social benefits or costs from a project. An economic analysis attempts to include society's valuation of benefits and costs through the use of shadow prices or by expanding the analysis boundaries beyond the individual level.

Social accounts is a term referring to the many costs and benefits of a project that cannot be monetized but still have significant social impacts that need to be considered. Social accounting techniques combine monetary and nonmonetary measures (e.g., social change, environmental, health, and institutional impacts) in their analyses. Two methods are *cost-effectiveness,* a type of social accounting that describes the monetary costs for a project per physical units of benefits, such as costs per person served or costs per unit of pollution reduction (Gittinger 1982); and an *appropriateness index,* a form of social accounting that arrays a variety of impacts from a project, perhaps assigning weights for different categories, to determine if a project is appropriate for the society. These impacts may include employment generation, infrastructure expansion (roads, bridges, buildings), use of local raw materials, monetized costs and benefits, and health, environmental, or sociopolitical effects (Santerre and Smith 1982).

An **environmental impact statement** (EIS) primarily describes and quantifies in physical, social, and, if possible, monetary terms the environmental impacts of a project. An expanded EIS includes the economic, health, safety, and social impacts of a project's environmental effects (Hufschmidt et al. 1983).

Any project has many types of impacts: economic, social, environmental, and political. Financial and economic analyses are concerned with measuring the monetary impacts, private or social costs, for a project. A financial analysis, sometimes referred to as a private market analysis, takes the perspective of a private entity (e.g., business, firm, or organization) and considers only the current or real prices it pays or receives in the private market. As discussed later, a common error in a financial analysis is to confuse the use of real (current costs minus inflation) and current money values for goods and services. In contrast, an economic analysis uses social values—"shadow prices"—for some benefits or costs to reflect what society feels are the project's actual benefits and costs. Given the problems of fully valuing the monetary costs and benefits of some impacts, economic analysis may use weights to subjectively reflect how society wants to value a benefit or cost stream. Social accounting techniques and environmental impact statements consider noneconomic impacts of a project and use a broader set of criteria to judge a project (Santerre and Smith 1982, Gittinger 1982).

This manual focuses primarily on financial analysis and to a lesser extent on economic analysis of energy fuels and technologies. Social and environmental analyses are equally important to a feasibility study but will not be discussed here. Given these various market perspectives, a project's benefits and costs are valued differently, as discussed in the next sections.

PROJECT COMPARISONS

An important part of a project is choosing what benefit and cost streams to compare. An analyst generally is required to allocate funding among different projects, so he or she usually has to choose the socially optimal project or projects. Two common methods are used to compare projects for a Pacific community or elsewhere.

Before and after, a common but erroneous method of project analysis, compares the net worth of the project after its adoption to the net worth of the situation before. The method should be avoided because a before-and-after comparison ignores expected changes in the before situation that will occur over time by keeping benefit and cost streams static.

With or without, in contrast to the before-and-after method, examines what will happen over time in a household, community, or region without the project or with the project. It compares the net worth of the situation without the project to the net worth of the situation with the project. This method adjusts for changes over time.

PROJECT TIME HORIZON

Time is critical to any project's expected benefits and costs because present dollars, kina, or tala (money) are preferred over future money. In project analysis, three types of analysis can be distinguished by how they treat time.

A **first-year cost** analysis, also referred to as **first-year returns**, includes only the benefits and costs incurred in the first year of the project. An **annual cost** analysis expresses benefits and costs as average annual values showing typical costs or benefits expected per annum over the life of the project. Annual averages do not show yearly fluctuations in benefit and cost streams. A **discounted cash flow** (DCF) analysis shows life-cycle costs as benefits and costs are incurred in each project year.* A DCF adjusts the benefit and cost streams incurred after year 1 by a discount rate to reflect the present valuation of future streams; that is, a DCF adjusts for time. The **discount rate** is the value placed on having money in the present rather than postponing its use until the future.

The treatment of time in a financial or economic analysis is critical to how benefits and costs are portrayed in a project. The major concerns in a first-year cost analysis are the front-end costs and revenues. This type of analysis gives an investor a feel for the cash flows needed in the first project year. In an annual cost analysis, the analyst is simply getting a feel for average benefits and costs that could be expected during the project's life. Yearly fluctuations and time patterns in the benefit and cost streams are ignored in this type of analysis.

In contrast, a cash flow analysis gives the exact benefits and costs as they are incurred each year. Such an analysis allows variation in the cost and benefit streams between years. The DCF incorporates a time value of money into the flows. Because future benefit and cost streams have been discounted to reflect their present-day valuation, discounted cash flows can be summed over time to give net present values. (See discussion on the time value of money and decision criteria on pp. 25 and 32.)

A DCF analysis is used in projects to show the actual patterns of benefits and costs as they are incurred over the project life. By reporting the particular cash streams for a given time period (e.g., year, month, five-year interval), the major factors influencing benefit and cost streams can be seen. Such factors include inflation, price changes, and risk or uncertainty. The DCF's ability to change key benefit and cost streams due to projected or conjectural price changes is a useful and instructive characteristic of a cash flow analysis. Besides conducting price sensitivity analyses, a DCF also has the advantage of showing the year or years in which benefits or costs change. For example, the benefits (sales) from a fast-growing wood plantation are not received until at least three or more years after planting. A DCF is more precise than an average annual cost analysis, since the latter evens out the impacts of lumpy net benefit streams.

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* Nondiscounted cash flow (NDCF) statements can also be made, but they do not discount cash flows (after year 1 to present values) and are used in calculating simple paybacks. Because an NDCF does not discount benefit and cost streams over time, the NDCF is technically wrong to use with any project analysis with a project life beyond year 1. Unfortunately, it is used because of its simplicity. It can be severely misleading to use it when a project occurs over time.

VALUING BENEFITS AND COSTS

The benefits and costs of a project can be measured in economic, environmental, and social terms. Quantifying benefits and costs in monetary or economic values involves the following steps:

1. Identifying the benefits and costs arising from the physical effects of a project;
2. Measuring the monetary values of benefits and costs;
3. Putting all the values into similar or constant monetary (dollar) terms; and
4. Comparing benefit and cost streams of the project.

First, the analyst must list all project benefits and costs. The benefits of an energy project are usually the revenues from selling the energy and/or the displaced fuel savings. Costs are the capital and operating costs. Thus, a project has **benefits** (B), which are revenues from sale of energy, electricity tariff revenues, or displaced fuel savings (costs for producing energy from the previous or alternative fuel). The project has **costs** (C), which are capital costs (fixed), e.g., costs for equipment, interest, installation, and fixed capital, as well as operating and maintenance (O+M) costs, variable or carrying costs, for annual fuel bills, repairs, labor, management, and administration.

Depending on the market perspective, an analyst uses different methods for valuing benefits or costs. **Private market (cash) values** are the current, usually cash, values placed on a project's benefits and costs by the private market. Only private market values are used in a financial analysis. **Shadow values,** the actual values society places on a benefit or cost, illustrate the *social opportunity cost* of a good or service. Since shadow pricing may not fully monetize society's valuation of a benefit or cost, the prices admittedly are difficult to estimate (Hufschmidt et al. 1983). An economic analysis generally includes some shadow-valued benefits or costs along with market prices for goods that have no externalities. **In-kind values** are the many goods and services used in or produced by a project that may be traded outside the formal cash market in a barter economy. These in-kind transfers may have both private market and social opportunity values. A **weighted valuation** is a form of shadow pricing since total benefit or cost streams can be raised or lowered to reflect society's preferences for a group of benefits or costs. Since weighting is quite subjective and seriously affects the project's outcome, weights need to be used with care (Mishan 1983).

The type of valuation used depends on the type of project analysis and is always difficult in a project because monetary values may be inaccurate or may not exist for many "benefits" or "costs." Private market values are naturally the simplest to obtain and are extremely important to investors since that group or individual wants positive net returns. Financial analyses include only private market values and should be made for every project.

Unfortunately, private market values may not necessarily reflect the full value to society from a good or service. In such cases **social values**, referred to as shadow prices, need to be estimated. Economic analyses usually include some social values, use of weights, or extension of the analysis beyond individual investing unit. An example is fuelwood's real cost to society in a deforested region. Wood's private market price may not include the eventual costs to society of replanting trees, the lost agricultural or timber revenues due to lower land productivity, and the dredging or silt removal costs due to soil erosion.

Because environmental costs associated with many renewable fuels are usually indirectly paid by society through organizations like a Ministry of Natural Resources, Forest Service, or Public Works Department, these social values are often difficult to quantify and enforce for the private user. While this manual will not show how to derive actual values for social costs or benefits, it will mention important ones to consider with particular fuels and technologies. Hufschmidt et al. (1983) present in-depth discussions of methods for assessing environmental and social shadow prices for natural resources.

In-kind transfers in an informal exchange or barter system are values that should also be included in project analyses. Often, these in-kind benefits and costs within a community, such as an exchange of labor services or wastes (e.g., dung or crop residues), are extremely important to a social system for welfare, cooperation, and cohesion. In order to account for such exchanges, in-kind transfers should be monetized whenever possible and entered in an analysis. Both their private and social opportunity costs could be used to reflect a financial and economic perspective.

Finally, another indirect form of valuation is the use of **weights** on a particular benefit or cost stream or for a group of streams. Weighting is used in economic analysis when project analysts believe the private market value does not reflect how important or unimportant it is to society (Gittinger 1982). For example, equity weighting is commonly used in social cost analyses that break down the benefits and costs of projects by particular income groups (Irvin 1978). If one objective of the project is improving the welfare of lower income groups, higher weights may be assigned to this group's benefit and cost streams. Weighting will not be used in the project analyses of fuels and technologies but should be recognized as one means of incorporating nonmonetary objectives into financial and economic analyses.

Time Value of Money

Money has a time value associated with its use because it can earn interest (or yield a return) if saved or invested. Interest rates are the private market's value on time. It is the value of using money in the present rather than postponing its use until the future. Inflation is used in a project analysis when certain benefit or cost streams are expected to increase or decrease faster than the average price growth rates.

A DCF benefits-and-cost estimation involves **discounting** or **compounding** through the use of interest rates (interest plus inflation if current prices are used). To calculate the future worth or value (FV) of a present amount of money, compounding is used; to calculate the present value (PV) of future money, discounting is used. Both compounding and discounting incorporate time effects into benefit or costs streams (Gittinger 1982). Compounding projects into the future the value of a present day amount after compounded interest has been added into the principal. Discounting takes future money streams and brings them back into present day value by removing the interest (or interest plus inflation) factor.

These methods are means of incorporating a time value of money into or out of cash flows. Gittinger's (1982) equations for compounding and discounting factors are

Compounding Factor

$$FV = PV(1+i)^n \tag{3.1}$$

Discounting Factor

$$PV = FV \frac{1}{(1+i)^n} \tag{3.2}$$

where FV = future value of benefit or cost

PV = present value of benefit or cost

i = interest rate or discount factor

n = years

The value of time is incorporated in a discounted cash flow analysis by several terms: interest rate (current or real), inflation, and discount rate. Interest, in a general sense, is the return on investment capital expected by an investor, e.g., government sector, private industry, or financial institution. Given that the value of money may inflate over time due to inflation in the country's money supply, several interest rates can be given. A **real interest rate** is the rate of return on capital without inflation. Real interest rates are used when all project prices are reported in constant dollars (e.g., when inflation is excluded). The **current (nominal) interest rate** is the rate of return experienced by the investor in the market that includes inflation; that is, the current rate is the sum of inflation added onto the real interest rate. The simple equation relating real and current rates is*

$$\text{Current Interest Rate} = \text{Real Interest Rate} + \text{Inflation} \tag{3.3}$$

For example, the real interest rate may be 4 percent, but given an 8 percent inflation rate the current rate is 12 percent. The **private discount rate**, used in compounding or discounting, is either the real or current interest rate depending upon the exclusion or inclusion of inflation, respectively. If a project analysis uses all real (constant) terms for the cost of capital, it must not inflate the annual operating and maintenance costs and benefits and must use a discount factor equal to the real interest rate (Table 3.2). However, a discount rate equal to the current rate is used if current prices and interest rates for O+M and capital, respectively, and inflation rates are used on benefits and costs after year 1. A summary of the correct rates to use in the different types of DCFs is given in Table 3.2. Inconsistency in terms is the most common mistake made in a project analysis. By mixing real and current rates or prices, capital and O+M flows are distorted. Real rates and prices are generally preferred. Most project analyses put costs and benefits in real terms, although real rates for capital are

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* This simple equation can be adjusted to become a more complex equation in precise financial studies.

Table 3.2. Appropriate Interest, Inflation, and Discount Rates to Use in Current Versus Real Discounted Cost Analyses[a]

Rates	DCF Based on Real Costs	DCF Based on Current Costs
Interest	i = real	i = current
Inflation	inflation rate = 0	inflation rates > 0
Discount	discount = real i	discount = current i

[a] Current = nominal (real + inflation).

not directly observed, because capital-intensive projects may be favored with the use of current rates (inflation). A further complication in determining the proper discount rate is the use of a private (current or real) versus social (public sector opportunity costs) rate. Such distinctions are made in financial versus economic analyses, respectively, but will not be discussed here (see Gittinger 1982, Gregersen and Contreras 1979, Mishan 1983).

Treatment of Capital

Capital expenditures for equipment and installation are a significant cost component of energy conversion technologies. Several options are available to a project analyst in reporting capital payments on an average or annual basis. The use of different options depends upon the type of financing, the financing group, and the accounting procedure used in the analysis.

First, capital expenditures can be financed through internal cash funds (equity) or debt financed by taking out a loan. If a loan is needed to finance the project's capital expenditures, the borrower must pay a debt service equal to the interest paid on the principal in addition to paying off the principal. A variety of methods exists for determining annual debt service payments (see Aplin et al. 1977). For present purposes, it is important to recognize that a debt service must be paid over time by the borrower.

The second point regarding the treatment of capital in financial analysis is that the borrower may or may not be the group maintaining and operating the system. In a private-sector investment, the borrower is usually the same as the investment or user group. Thus, this investing unit pays the debt service. In a public sector or aid-sponsored project, however, the borrower is often the government or aid donor while the user is the community, household, or public institution. As the loan recipient may not need to pay off the loan, a debt service should not be included in a financial analysis of a project with outside financing. In contrast, debt service payments are included in the financial analysis for the government.

Regardless of debt or equity financing, every project usually replaces the capital equipment at the end of its productive life. Gradual repayment or writing off the original investment is called **amortization** (Gittinger 1982). Several forms of amortization exist, including **depreciation** and **capital recovery factor.** Depreciation is used for tax purposes when capital is being written off and should usually not be used in project analyses. It takes the original capital cost, subtracts the salvage value of the equipment, then divides by the life of the asset; the equation for **straight-line depreciation** is:

$$\text{Depreciation} = \frac{\text{Capital Cost} - \text{Salvage Value}}{N} \tag{3.4}$$

where

N = life of asset (years)

Depending upon the rate of amortization desired, other depreciation methods are also used (Aplin et al. 1977). A problem with depreciation is that it does not account for replacement costs. As explained previously, the cost of money is expected to grow in future years at a certain rate, the interest rate (i). The capital recovery factor, another form of amortization, includes an interest or money growth component as well as a principal or amortization component (Gittinger 1982). The capital recovery factor is preferred if the project wants to be self-sufficient and replace the equipment in future years. The capital recovery factor formula is:

$$A = P \frac{i(1+i)^n}{(1+i)^n - 1} \tag{3.5}$$

where

A = equal payment

n = each period

P = principal

i = interest rate

An important problem in replacing the original asset is that unless the cost of the asset has increased at the rate of interest, future replacement costs will not equal the sum of capital charges set aside over the asset's life. This problem can be avoided by using an average inflation rate for the price of the asset in the formula rather than the prevailing economy-wide interest rate.

In a financial analysis, capital costs will always include a capital recovery factor based upon capital expenditures and an expected money growth rate. In contrast, in an economic analysis, total capital expenditures are accounted for when they occur in a project. Interest is not included in an economic analysis because it represents transfers within the economy (Gittinger 1982, Irvin 1978).

Benefits and Costs in Financial Versus Economic Analyses

As discussed previously, the types of benefits and costs differ in a financial versus economic analysis. As a financial analysis is concerned with a private market perspective, such an analysis takes the existing private market values for benefits and costs. In contrast, an economic analysis is concerned with social valuations of benefits and costs of a project.

The distinction in treatment of benefits and costs in financial versus economic analyses can be seen in Table 3.3. One important difference is that the full costs of fuel production (e.g., without government subsidies) are used in an economic analysis. Second, capital is treated differently, and full capital expenditures (in both the benefit and cost categories) are accounted for when they occur in a project in an economic analysis compared with annual payments in a financial analysis. Since society incurs the debt the year that the expenditure occurs, this rationale is used to justify such treatment in the economic analysis of capital costs. In contrast, in a financial analysis, the investor can spread the costs of capital over the project life.

Third, the use of shadow prices for labor, fuel (nonsubsidized prices), foreign exchange, and land rental is also common practice in an economic analysis. Shadow pricing the foreign exchange costs is particularly important in capital-intensive projects where energy technologies are imported. Shadow pricing the foreign exchange component entails determining the percentage of the total capital, or O+M costs, imported and thus paid for with foreign exchange, then multiplying this amount by a foreign exchange factor (Siwatibau 1981):

$$\text{Foreign Exchange Shadow Value} = \text{Total Cost} \times \%\ \text{Imported} \times \text{Foreign Exchange Factor} \qquad (3.6)$$

A common foreign exchange factor is about 1.15–1.40 in most Pacific island countries (Siwatibau 1981). This factor implies that the cost to society of importing a dollar's worth of goods is 1.15 times the cost of using the same dollar for buying domestically produced goods. Fourth, taxes or other transfer payments between groups are not included in

Table 3.3. A Comparison of Typical Benefits and Costs of Energy Projects in Financial Versus Economic Analyses

Benefits and Costs	Financial	Economic
Benefits = fuel savings		
Capital savings[a]	Annual capital charge	Total capital expenditure in year capital expenditure is incurred (foreign exchange shadow priced)
O+M savings	Fuel (subsidized cost)	Fuel (full costs of production)
	Labor (private market wage rate)	Labor (shadow wage rate)
	Maintenance, repairs	Maintenance, repairs (foreign exchange shadow priced)
	Freight charges	Freight charges
	Taxes	No taxes
		Environmental benefits
Costs		
Capital costs[a]	Annual capital charge	Total capital expenditure in year capital expenditure is incurred (foreign exchange shadow priced)
O+M costs	Fuel (subsidized cost)	Fuel (full costs of production)
	Labor (private market wage rate)	Labor (shadow wage rate)
	Maintenance, repairs	Maintenance, repairs (foreign exchange shadow priced)
	Freight charges	Freight charges
	Taxes	No taxes
		Environmental costs

[a] Capital expenditures should include equipment, installation, engineering, and siting costs. Debt servicing is optional depending upon the investor (private versus public or aid donor) and financing mechanism.

an economic analysis because taxes are viewed as transfers within the economy but do not represent additions to or subtractions from the economy's production of total goods and services. Finally, income distribution effects are a further distinction often made in an economic analysis.

The following example illustrates common annual average benefits and costs of an energy project using a financial market perspective (Energy Mission Reports 1982).

Example:

A palm oil mill in the Solomon Islands is interested in using its excess waste, palm oil effluent, in a biogas digestor to produce gas to run gas engines. The digestor-produced energy would be sold as electricity at a price equal to the central electricity authority's price. Annual average benefits and costs of the project are expected to be:

Benefits (annual)	SI$/yr
Electricity sales per year (1.22 GWh/yr, 10SI¢/kWh)	122,000
Total benefits per year	122,000
Costs (annual)	
Capital charge (10% per yr)	
Equipment	23,140
O+M	
Fuel and labor	12,000
Gas generator maintenance	19,500
Biogas digestor maintenance	8,000
Total costs per year	62,640
Net annual benefits (benefits – costs)	59,360

TYPE OF COSTING

The two ways of reporting benefits and costs are as averages or incremental (marginal) changes. In an **average cost analysis,** benefits and costs are given as full costs incurred for a given time period in costs per unit time. A **marginal cost analysis** looks at incremental or net changes in benefits and costs for the time period. A marginal cost analysis compares project benefits and costs to something, e.g., past costs, alternative project costs, or to each other (net benefits to net costs).

An average cost analysis looks at the average costs and/or benefits that result from a project. A marginal analysis, in contrast, needs to compare costs and benefits to some other factor. This standard for comparison may be costs of another project (e.g., the marginal gain or loss from wood stoves vs. kerosene stoves) or the previous year's costs or benefits (net changes between years). Both average or marginal costs could be used when conducting a first-year, annual, or cash-flow analysis. For example, the most common combinations are first-year averages, annual averages, and marginal or average cash-flow statements.

DECISION CRITERIA

Finally, a project analysis must compare benefits and costs to judge the financial or economic feasibility of a project. A basic question for the analyst is: What criteria will be used to decide to reject or accept a project? Comparing projects and assessing project worth require some common rules for comparisons, and in project analysis these rules are called **decision criteria.** Use of various decision criteria depends upon the time frame in the analysis (first-year, annual, or cash flow), type of analysis (financial, economic, or social accounts) and characteristics of the project. Some important project characteristics are funding limitations, fluctuations in cash flow, and possible user charges (Gittinger 1982, Mishan 1983). A wide variety of decision criteria are used in project analysis.

A **break-even analysis** finds the value for a particular cost or benefit stream that makes the net benefits (benefits minus costs) equal to zero (Gittinger 1982). It is the value for a cost or benefit (or groups of costs or benefits) at which the project breaks even. A break-even price for either a benefit or a cost stream can show us how well we must do in order for the project to be attractive. A break-even analysis can be used in all three types of time cost analysis—first-year, annual, or cash flows—and in financial or economic analysis.

Benefits minus costs or **net benefits** (B–C) are the inflows subtracted from the outflows of a project (Gittinger 1982). The benefits-minus-cost selection criterion is that a project is chosen so long as the net benefits (NB) are greater than or equal to zero (i.e., nonnegative net benefits). This criterion can be used in first-year or annual cost analyses since it does not necessarily include discounting. The **net present value** criterion, a discussion of which follows, is a type of NB and is used for cash-flow analyses.

Net present value (NPV), or **discounted net benefits,** is the present or discounted value of the benefits of a project less the present (discounted) value of the costs. The NPV is a subset of the B–C in that NPV is a measure of discounted project worth; it is used when projects exceed one year but has some limitations (Gittinger 1982). The selection criterion for the NPV is the same as for a B–C: a project is chosen if its NPV is greater than or equal to zero.

Incremental net benefit or **incremental cash flow** is the increase in net benefits with the project as compared with the net benefits in a case without the project or with a different project. It is simply the net benefits of one project subtracted from the net benefits of an alternative project. A project is selected over an alternative project if there are positive incremental net benefits. An incremental net benefit criterion can be used in first-year, annual, or cash-flow cost analyses. Although not quite accurate theoretically, it is a criterion often called a "marginal cost analysis." Both financial and economic analyses could use the incremental net benefit measure.

Benefit/cost ratio (B/C) is the benefits divided by costs of a project. As discounted benefits and costs are always used in cash-flow analyses, it compares the present value of benefits to the present value of costs. The selection criterion for the benefit/cost ratio is to select all independent projects with a benefit/cost ratio greater than or equal to one (Gittinger 1982). The benefit/cost ratio is commonly used in a cash-flow analysis, and annual or first-year cost analyses. Both financial and economic analyses employ the benefit/cost ratio for ranking projects but like the NPV, the B/C has particular limitations that should be examined (Gittinger 1982).

The **simple payback period** determines the project year in which the project's capital expenditures (investments) are recovered, i.e., when revenues (benefits) pay back the original capital expenditure. It is used in a nondiscounted cash-flow analysis, which is an incorrect type of financial analysis since it ignores the time value of money by not discounting. The simple payback period is mentioned here only to point out that it is still used too often although it is misleading and incorrect.

A **discounted payback period**, similar in concept to the simple payback criterion, finds the year in which the capital expenditures are covered by the discounted benefit streams. It is used with discounted cash-flow analyses, generally in a financial analysis where a firm or investment group is interested in recovering its investment. This criterion is *the only correct payback period* that should be used in cash-flow analyses.

The **internal rate of return** (IRR) is the discounted rate that sets the present value of the net benefit streams (discounted benefits minus discounted costs) equal to zero. The selection criterion is to accept a project with an internal rate of return that is greater than or equal to the cost of capital. The internal rate of return is used in a discounted cash-flow analysis but may be incorrect to use if net benefit streams change signs over time and cause the project to give multiple IRR solutions (Gittinger 1982).

Cost-effectiveness is used in a social cost analysis in which all benefits cannot be monetized fully but are known in physical or social impact terms. Cost-effectiveness may relate quantifiable costs of a project (e.g., pollution abatement costs) to benefits (e.g., lives saved). The least-cost criterion selects the project with the lowest costs that gives the same amount or types of benefits (Gittinger 1982).

Each decision criterion has specific limitations that will not be discussed here but are important to proper use (Gittinger 1982, Mishan 1983, Commonwealth Secretariat 1982, Hufschmidt et al. 1983). Formulas on calculating these decision criteria are presented in Appendix C along with the criteria to accept or reject a project.

RISK AND UNCERTAINTY IN RENEWABLE ENERGY PROJECTS

The very nature of renewable energy projects contains a wide degree of risk or uncertainty. Strictly defined, **risk** exists when probabilities of an outcome are known, whereas **uncertainty** exists when such probabilities are unknown. For example, we may know that there is a 50 percent chance that diesel prices will rise by 10 percent next year (risk) but really are not able to predict the effect of rising diesel prices on the costs of fuelwood (uncertainty). Simple methods for incorporating risk or uncertainty in project analysis vary, depending upon project characteristics (e.g., capital vs. labor), length, and size (Gowen and Morse 1981). In fact, projects may need to be redesigned or expanded to include less risky factors if the original project contains too high a degree of risk or uncertainty.

Because renewable energy projects are relatively new to the Pacific, their perceived risk or uncertainty is often higher than for well-known, though not necessarily more efficient, fossil-fuel systems. For instance, the energy production and supply sides for fuelwood involve much uncertainty with regard to future wood prices, supply contracts, and even land tenure problems for large energy systems. Given the lack of previous experience with biomass, the real versus perceived risks may be substantial but unknown until pilot projects are undertaken. It is this perceived risk factor that must be examined and not underestimated by energy analysts when presenting and designing energy strategies that include biomass components. The familiar is always more secure, and for these reasons accurate resource, economic, and risk assessments are critical for making decisions that are realistic and will not jeopardize future renewable energy projects.

PROJECT ANALYSES OF FUELS AND TECHNOLOGIES

In the following chapters, first-year, annual average, and cash-flow statements are given for various fuels and technologies based upon systems used in the Pacific. These costs generally come from the Energy Mission Reports (1982), adjusted for inflation and varying assumptions. Most analyses use simple financial (private market) values, and there is limited reference to possible social benefits or costs that might be considered in an economic analysis. The objective of the economics provided in this manual is to give general, not definitive, estimates. Simple tools are used because cost data are quite limited in the Pacific for most renewable energy systems.

4

ENERGY RESOURCE ASSESSMENTS

Nonfossil energy sources such as wood, crop residues, and moving water have always been used for energy production in rural and urban areas. Interest in increasing their use and improving the technologies that utilize these resources is a result of real cost increases for imported fossil fuels. If socially and economically acceptable, local energy resources can partially replace foreign-fuel dependence, and local development is encouraged.

This chapter shows how to make resource supply assessments for nonfossil fuels. It presents equations, data, and brief discussions of energy resources in the tropics. These resources—forestry, agricultural, animal or solid wastes, solar, water (hydro), and wind—are important to the tropics because of their large supplies and, often, their familiarity.

This chapter provides a description of each resource (e.g., its advantages and disadvantages), followed by a set of general resource assessment equations and typical data on various energy characteristics of the fuels. Due to their abundance and current use, biomass fuels are covered in some detail in the first section. A section on estimating solar energy potential follows the biomass section. Methods on conducting hydro and wind resource assessments are then given in the final two sections.

An energy resource assessment determines the potential amount of a resource, or the supply of it, that can be used to produce energy. As shown in Chapter 2, a resource assessment is the first step in making an energy assessment, with the technology assessment (Chapter 5) as the second step.

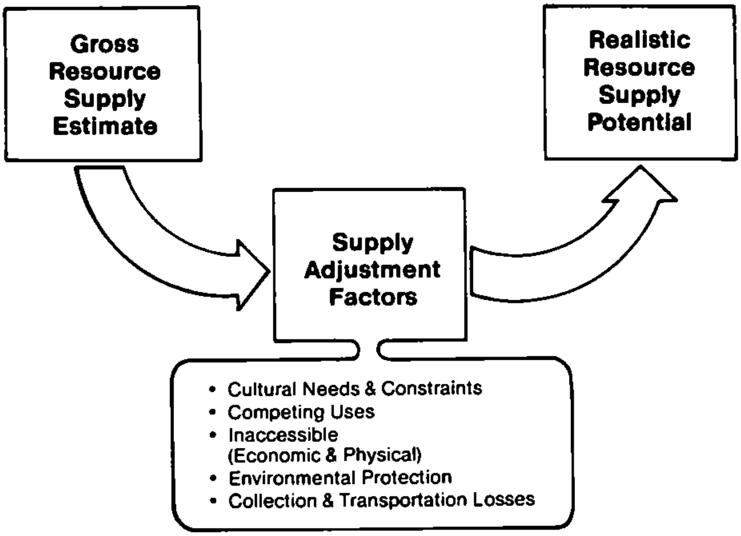
Gross Resource Supply Estimate
Supply Adjustment Factors
Realistic Resource Supply Potential
• Cultural Needs & Constraints
• Competing Uses
• Inaccessible (Economic & Physical)
• Environmental Protection
• Collection & Transportation Losses

Figure 4.1. Resource assessment steps.

A resource assessment first finds the "gross" resource supply in an area, region, or country, then adjusts this "gross" value to give a realistic supply estimate. Realistic values, not gross figures, are needed by energy planners and policymakers to develop sound energy strategies. Figure 4.1 shows the general steps involved in making a resource assessment. All gross estimates are modified by adjustment factors to give the realistic potential. This then tells the energy planner what to expect realistically from any given energy resource. These adjustment factors are critical when calculating biomass energy supplies.

BIOMASS RESOURCE ASSESSMENT

Biomass fuels are defined here as organic materials that are combustible or fermentable. Biomass includes forestry, agricultural, and animal or solid waste material. Within these categories, crop residues and biomass-derived fuels such as charcoal will be discussed. The Energy Mission Reports (1982) found biomass fuels to have the largest nonfossil fuel potential for nine Pacific island countries.

Biomass fuels are attractive to many Pacific countries for several reasons. First, biomass–coconut shells, trees, and crop residues–is abundant in the tropics. Second, properly managed biomass fuels are renewable and thereby can provide a sustainable energy supply for a country. Given the rapid growth rates for plants in the tropics, biomass plantations may provide an important long-run sustainable supply of fuel. Third, the use of local biomass fuels may have larger internal benefits for the country than alternative nonfossil fuels (e.g., solar, wind, hydro). Biomass fuel use may foster more internal employment and public and private sector integration through having more local stages in production–biomass production, transport, and conversion–than a solar, hydro, or wind system of comparable size.

The format for the biomass subsections is (1) calculation of the physical resource potential after factor adjustment, (2) calculations for converting this physical base into common energy equivalents, and (3) presentation of empirical data on the fuel taken from tropical or Pacific islands research. The first two parts show a planner how to estimate the actual biomass energy potential, and the third part of each subsection gives relevant data to be used in the equations.

Forestry

Forest biomass is categorized as sustainable, overmature or "nonsustainable," and residues or residuals. A sustainable potential can be produced from the standing timber (mature trees) or brush. Examples are low-quality pine or hardwoods not suitable for timber or paper production. The harvest of this sustainable potential is limited by a tree's annual growth rate since the annual harvest rate must not exceed the annual growth rate. In contrast, nonsustainable resources are the forest's overmature, dead, or rotting trees, sometimes referred to by foresters as cull and senile trees. For instance, senile coconut trees on many plantations in the Pacific have potential for energy use. This biomass is nonsustainable because its harvest is not based on the life cycle or rotation length of the species but represents a one-time potential. Residues, such as coconut shells or husks, are a third source for forest-based energy.

The need for a sustainable/nonsustainable distinction results from different forest management schemes. Although there will always be some dead trees, proper forest management would ensure that dead or diseased trees in a forest, the nonsustainable portion, are kept at a minimum. Annual thinning could remove such overmature or diseased material. Private or public forests that have grown beyond their highest economic and wood production yields may have many overmature trees that could be harvested. Forest residue material may have a large energy potential in the Pacific islands because of the many senile coconut and palm trees. Residues come from commercial forests during logging, from nearby saw or pulp mills, or as by-products of the industry such as coconut oil, husks, and shells or palm oil. Logging and sawmill residues can be burned directly for heat or electricity while palm oil and coconut oil can replace liquid fossil fuels.

FACTORS AFFECTING FOREST BIOMASS CALCULATIONS

Several critical factors can raise or lower forest biomass estimates. The first major data problem is simply the units in which forest data are commonly calculated by a forest ministry. Most forest statistics measure a region's timber production using data in terms of *commercial* timber yields per area, in cubic meters (m^3) or cubic feet (ft^3). Since the portion of a tree that can be used for energy production—the biomass, i.e., limbs and whole trunk—is substantially larger than the commercial timber portion, either biomass data for the trees need to be obtained or commercial timber data must be increased by a timber: biomass conversion factor to reflect biomass yields. Thus, when the equations given for sustainable wood have the term "average biomass yields," biomass data and not commercial timber data should be used unless a factor for converting commercial timber into biomass is known for a particular species. Since biomass yield data may vary widely depending on the tree species, moisture content, and density, the analyst should use high and low estimates to give a realistic range of expected biomass energy potential.

A second factor affecting forest biomass estimates is the multiple uses for wood or nonwood (palm) species. In the Pacific islands there are important cash-generating alternative uses of coconut, pine, and palm trees such as timber (pine), oil, or copra. This means many trees will not be cut for energy use, and they need to be subtracted from biomass energy calculations to present short-term, or perhaps even long-term, estimates of the realistic sustainable tree energy potential. Since prices for commercial forest products (oil, pulp chips, or lumber) are generally higher than the market or imputed price for energy products, competing uses for sustainable biomass may make trees a low priority energy use in Pacific islands except low-quality, overmature, or senile trees. Forest industry residues such as sawmill wastes, coconut husks, shells, and waste oil may have high priority but limited energy potential to the islands.

Other factors may also lower forest energy estimates. These factors include the mix of forest cover or land management (plantation vs. small holdings) systems in an area, the soil protection requirements, the economic and physical accessibility of the resource, landowner attitudes toward harvesting, and losses during production, harvesting, and storage. The tree species to be used as a fuel also affects the biomass yields, harvest year, soil protection needs, the management system, and energy content. Each of these factors will be discussed in detail in the equations, which can be used in making resource and energy assessments for sustainable, cull-senile (nonsustainable), and residue forest material.

SUSTAINABLE FOREST BIOMASS EQUATIONS

Calculating sustainable forest energy is a two-step process. First, the annual, potential supply is estimated, and second, the physical supply is converted into the energy equivalents. For sustainable forest energy, average resource supplies are adjusted by biomass growth rate, the percentage of land in forests (forest cover) in the area, the permissible removal rate that still protects the soil and watershed, traditional levels of harvest in the area, realistic accessibility of the wood resource, competing uses, and collection losses. The sustainable supply is expressed either in wet weight (MT mcwb or t mcwb) when moisture content wet basis is used or oven-dry weight (od MT or od t) per year. Depending upon the use of wet or oven-dry estimates, in step 2 the potential supply is converted to its annual energy flow by multiplying the wet or oven-dry weight by the appropriate low or high energy content, respectively (see Chapter 2). Definitions for each term used in the equations are presented at the end of steps 1 and 2 along with their measurement units and possible local sources of data.

For step 1, the forest resource assessment supply estimate, the equation* is

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[*] The equations presented in this manual follow a general format which includes the appearance of applicable units under each term in an equation. Since both the SI and British systems are used in the Pacific, both sets of units appear, with the SI units first. Where only one unit appears, such as 0.xx for a fraction, the unit applies to both measurement systems.

Area (ha) (acre)	X	Annual Biomass Yield per Unit Area at Specified Moisture Content (MT od or mcwb/ha · yr) (t od or mcwb/acre · yr)	X	Fraction Land in Forest Cover in Area (0.xx)	X	Fraction Environmentally Permissible to Remove from Forested Area (0.xx)	X	Fraction Land Traditionally Harvested as Fraction Forested Area (0.xx)	X	Fraction Economically Accessible in Forested Area (0.xx)

X	Fraction after Collection Losses (1 − 0.xx)	−	Annual Competing Uses (MT od or mcwb/yr) (t od or mcwb/yr)	=	Annual Sustainable Forest Biomass (MT od or mcwb/yr) (t od or mcwb/yr)	(4.1)

For **step 2**, the sustainable forest energy assessment, the equations are

(a) Wet Basis Data (MT or t mcwb)

Annual Sustainable Potential at Specified Moisture Content (MT mcwb/yr) (t mcwb/yr)	X	Energy Content per Unit for that Specific Moisture Content (MJ/MT mcwb) (BTU/t mcwb)	=	Annual Sustainable Forest Energy (MJ/yr) (BTU/yr)	(4.2)

(b) Oven-Dry Data (od MT or od t)

Annual Sustainable Potential by Oven-dry Weight (od MT/yr) (od t/yr)	X	Energy Content per Oven-dry Unit (MJ/od MT) (BTU/od t)	=	Annual Sustainable Forest Energy (MJ/yr) (BTU/yr)	(4.3)

The energy analyst should be familiar with several terms relating to sustainable forest energy. **Area** is the region or area under consideration for energy production. The units are hectares or acres.

Biomass yield is the proportion of a tree or plant that can be burned or can be fermented into alcohol fuels. Biomass yields per unit area are usually higher than annual commercial timber yields because biomass includes more of the tree, trees grown for biomass can have closer spacing, and short-rotation energy crops have shorter cutting cycles. For instance, commercial timber includes only part of the tree trunk (the bole), whereas biomass includes the whole trunk, bark, limbs, and possibly roots. The units are wet (mcwb) or oven-dry MT/ha · yr or t/acre · yr. Local sources for this data are the forest service (ministry or department), or the energy department or ministry. Instead of using annual biomass yields, annual growth rates or mean annual increments can be substituted.

Forest cover is an important factor to consider in making a forest energy assessment. This is the percentage of the study area actually forested and at a harvestable age in the forested region. The analyst needs to adjust gross yield data for forest cover and age if the data on biomass yields per area do not already reflect actual forest density in the study region. In an energy plantation, all the area (100 percent) may be used for energy crops if all trees are the same age, i.e., if it is an even-aged stand. In a mixed-aged plantation there may be only 50 to 70 percent of the forest cover that could be harvested. In a country's regional resource assessment, adjustments for residential, agricultural, and forest lands are needed. The units are fractions (0.xx) of a total study area. The local data source is the forest service (department or ministry), maps, and forest statistics.

Harvest attitude is a term reflecting the fact that a certain percentage of forest lands, particularly small-holder plots, may never be cut for timber or fuelwood production. For instance, the landowner may not want to cut down the trees to use for fuel, or the land may be a national preserve. To adjust for landowner or planning attitudes, a realistic annual cut rate, say 20–50 percent of possible timber, could be used for fuelwood. This figure should come from conversations with the local forestry department and landowners. The units are fractions (0.xx) of the forested study area. The local data sources are the ministry or department of forestry or natural resources, which should have land tenure pattern information or timber industry data on harvest rates by landowner classes.

Environmentally permissible removal refers to the fact that given the frailty of tropical soils and the need for watershed or nature preserves, complete removal of some species may cause environmental problems. Thus, only a fraction (or none) of the trees may be cut in an area. To get this removal rate, the analysts should ask local foresters, soil scientists, and natural resource managers. The units are fractions (0.xx) of the forest study area. Local data sources are the ministry or department of forestry or natural resources.

Accessibility means that while a large area may be forested, part of it may not be physically or economically accessible for harvest. A rough estimate of what may be feasibly collected per year gives a more realistic figure for actual resource potential. The units are fractions (0.xx) of the forest study area. Local data sources are the ministry or department of forests or the division of public works where it is possible to get road maps and talk to foresters, landowners, and public work officials.

The term **competing uses** reflects the fact that all of the forest material available in a region may never be used as fuel due to competitive uses for the resource. If alternative uses (oil or timber) receive higher prices for the wood, only part or none of the forest biomass will be available for energy use. In a commercial timber area, there may be significant forest residues remaining that could be used as fuel, but equations for residues are given later. The units used to measure competing uses are MT/yr or t/yr. The local data source is the forestry ministry or department, which will have data on timber or tree crop industries, fuel surveys, or other annual uses (residential).

Losses are that percentage of any resource that will be lost during harvest, collection, or storage. An approximation of the loss (as a percentage of the total potential) is useful to include in these calculations. With biomass harvesting, probably only 5–10 percent is lost during harvest, but 40–50 percent is also lost in commercial timber harvest, and 5 percent is lost due to outside exposure during storage. The units are fractions (1 − 0.xx) of the harvest. The local data sources are the forest ministry or department and the timber industry.

Sustainable potential is the term reflecting the fact that proper resource management is needed with forest resources to ensure a long-run supply, that is, their sustainability. To maintain this supply and maximum production level, the annual harvest should not exceed the growth rate of a natural regenerative forest or the economic optimum production level of a fast-growing species.

Energy content is expressed by oven-dry (HHV) or wet (LHV) weight. (See Chapter 2 for equations.) It is important to use the correct energy content for the fuel at the specific moisture content when it is burned or fermented. Green or air-dried energy values (LHV) are generally 20–30 percent less energy content than high, oven-dry heat values (HHV). The units are MJ/MT mcwb or MJ/od MT (MMBTU/t mcwb or MMBTU/od t). The local data source is the energy ministry or department.

FOREST MANAGEMENT SCHEMES AND ENERGY POTENTIAL

The management scheme of a forest resource significantly affects the yields and hence the energy potential of an area. Plantations of short-rotation, fast-growing species planted and maintained for fuel production will have higher annual yields than small-holder plots of natural regenerative forests. Often when calculating the energy potential from a plantation, the number of trees and the yields per tree are used rather than as in Equation 4.1, where the area and yields per area are used. It could be assumed that plantation owners have (1) no objections to harvesting, (2) good accessibility, (3) already chosen a species with low environmental damage (perhaps even enhancing the soil, as with nitrogen-fixing species), and (4) minimal collection losses. Thus, the equation in step 1 may be simply

$$\begin{array}{llllll}
\text{Area} & \times & \text{Annual Yield} & - & \text{Competing Uses} & \\
(\text{ha}) & & (\text{MT od or mcwb/ha}\cdot\text{yr}) & & (\text{MT od or mcwb/yr}) & \\
(\text{acre}) & & (\text{t od or mcwb/acre}\cdot\text{yr}) & & (\text{t od or mcwb/yr}) & \\
= \#\,\text{Trees} & \times & \text{Annual Biomass} & - & \text{Competing Uses} & (4.1\text{a}) \\
 & & \text{Yield per Tree} & & (\text{MT od or mcwb/yr}) & \\
 & & (\text{MT od or mcwb/tree}\cdot\text{yr}) & & (\text{t od or mcwb/yr}) & \\
 & & (\text{t od or mcwb/tree}\cdot\text{yr}) & & &
\end{array}$$

However, an environmental factor may be needed in the equation if nutrients are not replaced, and a forest cover factor used if intercropping occurs. The rotation length is simply the cutting cycle with even-aged plantations.

In contrast to short-rotation energy plantation estimates, assessing the forest energy potential from an area with many small-holder plots mixed with agricultural and residential lands is quite complex. In such cases, most of the adjustment fractions given in step 1 need to be used. A problem in regional estimation is the mixture of tree species with different growth rates. This problem could be solved by separating out the percentage of sustainable potential coming from different tree species. A less accurate but simpler method is to use the growth rate of the dominant tree species. In a regional analysis, areas with different tree species such as coastal areas with mangroves and highlands or inlands with coconut palms generally need to be estimated separately to also accurately account for variations in other factors (e.g., environmentally permissible removal, accessibility, and harvest attitude). An analyst needs to be aware of such considerations as different management schemes or species composition to make proper decisions when estimating regional energy potential.

Example:

An energy planner wants to estimate the amount of fast-growing wood that could be used for energy on an island. Two sources of fast-growing trees exist—eucalyptus trees planted on individual small holdings and eucalypts grown on a large plantation. In both cases, much of the wood can be used as poles for construction purposes, but even after these needs are met, excess trees are a potential fuel for a wood-fired gasifier, steam generator, or boiler. Given these two divergent management schemes, the analyst should estimate each potential supply separately. Some basic assumptions are common to both management schemes:

- The LHV for eucalyptus wood is 14.6 MJ/kg at 20 percent mcwb, given an HHV of 19.0 MJ/od kg.
- The basic density of a eucalyptus tree is 400 od kg/m^3, so the adjusted basic density for the air-dried wood at 20 percent mcwb is 500 kg mcwb/m^3 [400/(1 − 0.2)].
- The average yearly production (mean annual increment) for eucalypts is about 20 m^3/ha · yr for well-managed trees.

The resource assessment for the small-holder private lands involves about 200 hectares that have some eucalypts, but these trees are dispersed and cover only about 30 percent of the area. Furthermore, after talking to landowners and retailers for the poles and examining the topography and harvesting operations, the analyst feels that only 60 percent of the trees are economically accessible. A 10 percent collection loss can be expected, the private landowner harvest rate on the accessible land will probably be 70 percent given other labor demands, and the construction industry will use 80 percent of the trees, leaving only 20 percent for energy use. The resource assessment for small-holder lands is as follows:

Physical Assessment

Annual Biomass Yield = (20 m^3/ha · yr) (500 kg mcwb/m^3)
= 10,000 kg mcwb/ha · yr

Annual Small-holder Wood Potential = (200 ha) (10,000 kg mcwb/ha · yr) (0.30) (0.60) (1 − 0.10) (0.70) (0.20)
= 45,400 kg mcwb/yr at 20% mcwb

Energy Assessment

Annual Small-holder Wood Energy Potential = (45,400 kg mcwb/yr) (14.6 MJ/kg mcwb)
= 663,000 MJ/yr

For the plantation lands, the resource assessment is less complicated because all the land is accessible and is expected to be harvested. But, like the private lands, there is a 10 percent collection loss. The total harvest is more economical if 80 percent is sold for poles and 20 percent remains for the energy facility. The resource assessment for a 2,000-hectare plantation is:

Physical Assessment

Annual Plantation Wood Potential = (2,000 ha) (10,000 kg mcwb/ha·yr) (0.90) (0.20)

= 3,600,000 kg mcwb/yr at 20% mcwb

Energy Assessment

Annual Plantation Energy Potential = (3,600,000 kg mcwb/yr) (14.6 MJ/kg mcwb)

= 52,600,000 MJ/yr

Summing the two sources of eucalyptus wood energy gives an estimated total energy potential of:

Total Eucalyptus Energy Potential = (663,000 MJ/yr) + (52,600,000 MJ/yr)

= 53,300,000 MJ/yr or 53.3 TJ/yr

SUSTAINABLE FOREST BIOMASS DATA

A problem facing many energy analysts in the Pacific is finding national or even regional data for making resource and energy assessments. Table 4.1 presents forest biomass data from the Pacific islands and Asia. Appendix D presents additional data on the regenerative, alternative use, and energy (HHV) characteristics of many trees and palms from Indonesia, Fiji, the Philippines, India, and Hawaii. Like most field data, values in Table 4.1 and following tables represent averages with possible ranges of ±15 percent. Actual yields and energy content of a tree at any given site may vary widely due to site (soil) quality, topography, rainfall, and forest maintenance practices. Pilot projects are always needed for actual species selection.

Some general patterns can be seen in Table 4.1. First, a fairly narrow range of HHVs (18–22 MJ/kg) is typical for most species, with the exception of pine. What is most important to an analyst will actually be the air-dry weight and moisture content of the species prior to burning. Such weights and associated energy contents provide the actual input energy of the forest fuel. These values can be estimated using the equation for calculating LHV from HHV as presented in Chapter 2. Using the 18–22 MJ/od kg weight and assuming a 30 per-

Table 4.1. Average Energy Content, Rotation Length, and Annual Yields for Selected Tree and Palm Species

Trees/Palm Species (scientific name)	Annual Average Yield (m^3/ha · yr)[a]	Rotation Length (years)	Oven-dry Heat Content (HHV) (MJ od/kg)
Trees			
Acacia sp.	15–30	8–20	19–21
Albizia sp.	20–40	15	18
Cassia sp.	10–15	10	19
Casuarina sp.	5–15	15–20	21
Eucalyptus sp.	15–20	9	19
Leucaena sp.	15–50	2–5	19
Pine	5–20	15–20	20–28
Palms			
Cocus sp.	10	20	19
Mangroves			
Bruguiera sp.	5	30	18

Source: Appendix D.

[a] Higher yields are for intensive cultivation, whereas lower values are more typical under small-holder management.

cent air-dry moisture content of most wood in the tropics, typical LHVs fall to 12–15 MJ/od kg.

To choose appropriate forest species for an area, several selection criteria are important, and these fall into the basic categories of fuel production and use (Univ. of Philippines 1981).

- Production criteria
  - – low branchwood to stemwood ratio
  - – high growth rate (annual yields per unit area)
- Site adaptability criteria
  - – wide tolerance to different soils and climates
  - – habitat suitability to site under consideration
  - – low competition with alternative land uses (food, timber, oil)
  - – soil enhancer or enricher (nitrogen fixation)
  - – blowdown tolerance (close spacing capability and deep roots reduce blowdown problems)
- Regenerative system criteria
  - – fast growing, short rotation
  - – coppicing ability (ability to grow back branches from main

  - tree stem after harvest) rather than seed (natural) or planting regeneration
  - prolific seeder at early age if natural regeneration from seeds necessary
  - if artificial regeneration (manual seeding or planting necessary) then ease of production from planting stock, availability of good seed supply, or ability to sprout from cuttings needed
- Maintenance criteria
  - suppress weed competition
  - limited weeding and thinning necessary (low maintenance needs)
  - maintenance needs (weeding, thinning) fit community or landowner labor supply
- Harvest/transport criteria
  - easy to harvest, handle, process, store, and transport
  - harvesting not competitive with seasonal labor needs
- Economic/social criteria
  - economic to plant, maintain, harvest, and transport (cheaper than alternative fuels)
  - access to and existence of fuelwood markets
  - social acceptability of production, maintenance, harvest, and transport systems
  - social acceptability to fuel as energy source
- Energy values criteria
  - high energy value per unit volume
  - low energy "input to output" ratio (high fuel value but low energy needs per unit volume for production and transport)
- Complementary-use criteria
  - has supplementary uses such as intercropping, food, and animal fodder (leaves) and environmental benefits (nitrogen soil enriching)
  - wood could be used in variety of other markets (timber, paper) to increase future market options and reduce risk
- Wood fuel use criteria
  - ease of splitting and cutting
  - low smokiness and sparks
  - minimal pollution effects (low particulates, tars)

It is also helpful to categorize particular species with the various climatic and maintenance limits of the tropics. Some species with widespread adaptability fall into several categories. Categories used for these breakdowns are (1) growth, yield, propagation, energy; (2) soils, rainfall; (3) plantation type; (4) durability, maintenance; and (5) complementary uses. Species for these categories follow (Univ. of Philippines 1981, Brewbaker and MacDicken 1982):

- Fast-growing or high-yielding species
  - coppice regeneration:*
    - *Albizia falcataria*
    - *Calliandra calothyrsus*
    - *Cassia siamea*
    - *Eucalyptus urophylla*
    - *Gliricidia maculata*
    - *Leucaena* sp.
    - *Pterocarpus indica*
  - seed regeneration:
    - *Acacia auriculiformis*
    - *Acacia mangium*
    - *Acacia decurrens*
    - *Trema orientalis*
  - high energy content:
    - *Acacia auriculiformis*
    - *Acacia mangium*
    - *Acacia decurrens*
    - *Calliandra calothyrsus*
    - *Cassia siamea*
    - *Eucalyptus* sp.
    - *Gliricidia maculata*
    - *Leucaena leucocephala*
    - *Pterocarpus indica*
- Soils categories by rainfall
  - coastal/mangrove species:
    - *Avicennia officinalis*
    - *Bruguiera gymnorrhiza*
    - *Bruguiera parviflora*
    - *Bruguiera sexangula*
    - *Ceriops tangal*
    - *Rhizophora apiculata*
    - *Rhizophora mucronata*
  - coastal sands:
    - high-rainfall area:
      - *Casuarina equisetifolia*
      - *Eucalyptus camaldulensis*
      - *Eucalyptus tereticornis*
      - *Eucalyptus toreliana*

low-rainfall area:	*Acacia planifrons* *Acacia leucopholea* *Casuarina equisetifolia* *Casuarina junghuniana* *Palmyrah*
– poor sandy:	*Acacia auriculiformis* *Acacia decurrens* *Albizia leucopholea* *Calliandra calothyrsus* *Tamarindus indica*
– red loam:	
high-rainfall area:	*Albizia lebbeck* *Azadirachta indica* *Casuarina equisetifolia* *Eucalyptus* sp. *Leucaena leucocephala*
low-rainfall area:	*Acacia leucopholea* *Acacia planifrons* *Azadirachta indica*
– laterite:	
high-rainfall area:	*Pterocarpus indica*
low-rainfall area:	*Calliandra calothyrsus* *Casuarina junghuniana*
• Large-scale plantations	*Acacia auriculiformis* *Acacia decurrens* *Acacia mangium* *Calliandra calothyrsus* *Eucalyptus tereticornis* *Gliricidia maculata* *Leucaena leucocephala* (giant)
• Durability/maintenance	
– low maintenance:	*Acacia auriculiformis* *Acacia mangium*
– blowdown resistance: (low damage)	*Acacia mangium* (over *A. aurricul.*) *Eucalyptus tereticornis*

- Complementary uses or small-holder plots – homestead, marginal lands, intercropping:	*Acacia* sp. *Calliandra calothyrsus* *Eucalyptus camaldulensis* *Leucaena leucocephala* (common)

In summary, the selection of an appropriate sustainable forest species to be used for energy needs to consider a variety of fuel, environmental, end-use, and socioeconomic characteristics. Site adaptability and social acceptance are key to successful forest energy production.

NONSUSTAINABLE FOREST BIOMASS EQUATIONS

In areas where forests have been poorly managed in the past, extensive old-growth wood of various types may exist. While such trees are beyond their optimal commercial timber or crop (oil) potential, they can provide a nonsustainable (i.e., one harvest only) energy source. Harvesting this overmature wood both provides energy and improves the quality of the forest by allowing new growth or plantings to mature. Old-growth trees include cull (diseased, dead, and rotting) and senile (overmature) trees.

As compared with the sustainable forest potential, it is easier to calculate a nonsustainable energy resource by using the average number of senile or cull trees in a region. In the Pacific, old copra plantations are good sources for nonsustainable forest energy. Harvesting usually requires selective cutting rather than clear cutting if the old growth is of mixed ages. Accessibility, soil or environmental protection, and losses are still important adjustment factors in these assessment calculations. Competing uses (e.g., domestic cooking) may exist but be minimal and are not included in Equation 4.4. Forest cover and owner attitudes also are not included in the equation as they are not important to old growth harvest. In Equation 4.5 the *annual* cull or senile tree harvest is estimated by using a harvest rate that is realistic for the area. This rate is not the rotation length of the tree or palm species but a practical number of years in which to harvest the cull or senile trees. In Equation 4.6 it is critical to use the energy content and physical potential for the wood at its received (usually air-dry) moisture content. Data on energy content for cull and senile trees in the tropics are given later along with the data on forest residues.

For **step 1(a)**, the total resource assessment, the equation is

# Overmature Trees	X	Fraction Accessible and Environmentally Permissible to Remove (0.xx)	X	Usable Biomass per Tree (MT od or mcwb/tree) (t od or mcwb/tree)	X	Fraction after Collection Losses (1 − 0.xx)

= Potential Overmature (4.4)
(MT mcwb)
(t mcwb)

For **step 1(b)**, the annual potential, the equation is

$$\frac{\text{Potential Overmature (MT or t od or mcwb)}}{\text{Harvest Cycle (yrs)}} = \begin{array}{l}\text{Annual} \\ \text{Nonsustainable} \\ \text{Potential} \\ \text{(MT od or mcwb/yr)} \\ \text{(t od or mcwb/yr)}\end{array} \qquad (4.5)$$

For **step 2**, the energy assessment, the equation is

Annual Nonsustainable Potential (MT od or mcwb/yr) (t od or mcwb/yr)	X	Energy Content at Given Moisture Content (MJ/MT od or mcwb) (BTU/t od or mcwb)	=	Annual Nonsustainable Energy Potential (MJ/yr) (BTU/yr)	(4.6)

The analyst should be aware of terms related to nonsustainable forest biomass. **Overmature (cull/senile) trees** are old-growth (e.g., overmature or dead and rotting) trees that are beyond their optimum timber or crop (oil, copra) production. The units are the number of trees in the study area. The local data sources are the forest ministry or department and the timber or tree crop industry. **Accessible, environmentally permissible removal** refers to the environmental fragility of an area and accessibility of the trees. The units are fractions (0.xx) of total trees. The local data sources are the ministries or departments of forestry, natural resources, and public works.

Usable biomass yield per tree *may* be less than in the total biomass. Senile wood will generally have higher moisture content per unit volume than sustainable wood, thereby reducing its LHV below that for sustainable forest biomass. The units are mcwb or oven-dry MT (t) per tree. The local data sources are the forestry and energy ministries or departments. **Harvest cycle** is based on feasible removal rates of old-growth trees, cull or senile. The units are years, perhaps two to ten.

The local data sources are the forestry ministry or department or timber/tree crop industries. Local foresters and tree plantation workers also will know removal rates.

Energy content is important, because as noted previously, the high moisture content in cull or senile trees significantly decreases their LHVs per unit of wood. The units are MJ/MT mcwb or od (BTU/t mcwb or od). The local data source is the energy ministry or department.

Example:

A Pacific country's ministry of energy is interested in identifying all possible biomass energy resources. The head energy planner has already identified the eucalyptus energy potential, but the trees will not mature for at least five years. Thus, the planner wonders if an existing biomass resource could fill in the gap for the short term until the eucalypts mature. After a hurricane, there is significant blowdown damage on coconut plantations and many senile coconut trees from old plantations are affected as well. The resource assessment for the overmature and damaged trees is made using the following assumptions collected from secondary and primary data sources.

- The LHV for senile and damaged coconut trees is 10.3 MJ/kg at 40 percent mcwb, assuming an HHV of 19.1 MJ/od kg.
- The usable biomass per senile coconut tree is estimated at 1,000 kg mcwb/tree (Energy Mission Reports 1982).
- An estimated 6,000 senile or damaged coconut trees exist due to the hurricane and poor copra market conditions.
- About 30 percent of the trees are physically or economically inaccessible and about 10 percent of the biomass will be lost during collection.
- Local foresters estimate five years for harvesting the trees.

Using these data, the resource supply estimate is:

Resource Assessment

Senile Coconut Wood Potential = (6,000 trees) (0.70) (1,000 kg mcwb/tree) (0.90)
= 3,800,000 kg mcwb at 40% mcwb

Annual Senile Coconut Wood Potential = (3,800,000 kg mcwb/5 yrs)
= 760,000 kg mcwb/yr at 40% mcwb

Energy Assessment

Annual Senile Coconut Wood Energy Potential = (760,000 kg mcwb/yr) (10.3 MJ/kg mcwb)

= 7,800,000 MJ/yr or 7.8 TJ/yr

FOREST RESIDUE EQUATIONS

Raising tree species for energy production is only one potential source of forest-derived energy. Forest residues such as logging trash, shells, husks, branches, leaves, oils, fruits, and processing mill wastes can and often do provide energy in a country. Indeed, in the Energy Mission Reports (1982), coconut husks and shells were the largest energy potential among local fuels in the Pacific.

Residues are often the easiest short-term energy source for several reasons. First, the use of residues (e.g., coconut shells) often is complementary rather than competitive with timber or food (e.g., copra) production. Second, it makes use of a "waste" material, thereby giving added by-product income to the timber, pulp, or tree crop industry. Third, since these industries often include many small landholders, the income from residue sales goes directly to these people. Fourth, by creating another market (fuel) for a local resource, the price fluctuations in timber and cash crop markets may be offset by the possibility of additional energy incomes. Fifth, residue disposal by an industry may actually use energy or money. Thus, selling or converting the residues may save the plantation the energy or money used in residue disposal.

The use of residues, however, does have some problems. Because residues are a waste product of another industry, it may be expensive to coordinate residue harvest, collection, and transport in addition to the collection of the primary product. Second, if residues are waste products in a widely dispersed, decentralized system, then collection to a central user may be too expensive. This is particularly true for in-forest residues. For instance, with many small landholders the collection of coconut husks and shells at a central processing station may not be realistic or economical, whereas charcoaling the husks and shells on-site and then transporting the charcoal may be financially attractive. Thus, decentralized energy processing may be needed in some situations. If residues are produced where they are being used for energy (e.g., pulp or sawmills or copra plantations), the problem of centralized collection does not exist. Third, some residues may simply not be economically, environmentally, or physically accessible.

In summary, planning an energy supply around residue use must carefully consider the *feasible* potential.

Equations for estimating the residue energy potential are arranged by residue type: processing mill residues, logging field residues, coconut husks and shells, and oils. Processing mill residues include sawdust, slabs, chips, and other by-products at the industry site that can be chipped or used directly for fuel. Logging field residues generally are trash–excess limbs and small branches–that is left in the woods. Both accessibility and environmental protection are two factors that decrease gross estimates of logging field residues. The energy potential from coconut husks and shells can be calculated from data on either available trees and average nut production per tree or copra (dried coconut meat) production (Energy Mission Reports 1982). Both alternative calculations are given below. Finally, liquid fuels can be produced from tree or palm oils.

For **processing mill residues from saw or pulp mills, step 1(a)**, the physical resource assessment (air-dry potential), the equation is

Annual Pulpwood or Log Volume per Year (m^3 mcwb/yr) (t mcwb/yr)	X	Fraction Residues from Shavings, Off-cuts and Rejects (0.xx)	−	Competing Uses (m^3/yr) (t/yr)	=	Annual Processing Mill Residue Potential (m^3 mcwb/yr) (t mcwb/yr)	(4.7)

For **step 1(b)**, wet weight conversion to oven-dry basis, the equation is

Annual Processing Mill Residues (m^3 mcwb/yr) (t mcwb/yr)	X	Adjusted Basic Density (kg/m^3) (lb/t)	X	Oven-dry Weight per Air-dry Volume (od MT/kg mcwb) (od t/lb mcwb)	=	Oven-dry Processing Mill Residues (od MT/yr) (od t/yr)	(4.8)

For **step 2**, the energy assessment, the equation is

Oven-dry Processing Mill Residues (od MT/yr) (od t/yr)	X	Oven-dry Energy Content (MJ/od MT) (BTU/od t)	=	Annual Processing Mill Energy Potential (MJ/yr) (BTU/yr)	(4.9)

For in-forest **logging residues, step 1(a)**, the physical assessment (wet basis), the equation is

Annual Logging Volume (MT mcwb/yr) (t mcwb/yr)	X	Fraction Accessible Residue (0.xx)	X	Fraction Environmentally Permissible Removed (0.xx)	=	Logging Residues per Year (MT mcwb/yr) (t mcwb/yr)	(4.10)

For step 1(b), conversion to oven-dry basis, the equation is

Logging Residues per Year (MT mcwb/yr) (t mcwb/yr)	X	Oven-dry Volume per Wet Volume (od MT/MT mcwb) (od t/t mcwb)	=	Annual Oven-dry Logging Residues (od MT/yr) (od t/yr)	(4.11)

For step 2, energy assessment, the equation is

Annual Oven-dry Logging Residues (od MT/yr) (od t/yr)	X	Oven-dry Energy Content (MJ/od MT) (BTU/od t)	=	Annual Logging Residue Energy Potential (MJ/yr) (BTU/yr)	(4.12)

For coconut husks and shells, by tree data, for steps 1 and 2, the physical and energy assessment, the equation is

Coconut Palms (#)	X	Nuts per Tree Harvested per Year (#/yr)	X	Fraction Accessible (0.xx)	X	Average Shell or Husk Volume per Nut (kg mcwb/nut) (lb mcwb/nut)

X	Energy Content per Volume (MJ/kg mcwb) (BTU/lb mcwb)	=	Annual Husk or Shell Energy Potential (MJ/yr) (BTU/yr)	(4.13)

For step 3, the noncompetitive energy assessment, the equation is

Annual Husk or Shell Energy Potential (MJ/yr) (BTU/yr)	–	Husk or Shell Energy Use by Copra Industry (MJ/yr) (BTU/yr)	=	Noncompetitive Husk or Shell Energy Potential (MJ/yr) (BTU/yr)	(4.14)

For coconut husks and shells, by copra data, for step 1, the physical assessment, the equation is

(a)	Coconut Palms (#)	X	Harvested Nuts per Tree per Year (#/yr)	X	Fraction Accessible (0.xx)	=	Annual Coconut Production (#/yr)

(b)	Annual Coconut Production (#/yr)	X	Average Volume Dry Copra per Coconut (kg/nut) (lb/nut)	=	Annual Dry Copra Production (kg/yr) (lb/yr)	
(c)	Annual Copra Production (kg/yr) (lb/yr)	X	Average Husk or Shell Weight at mcwb per Copra Weight (kg mcwb/kg copra) (lb mcwb/lb copra)	=	Husk or Shell Weight at Given Moisture Content (kg mcwb/yr) (lb mcwb/yr)	
(d)	Husk or Shell Weight at Given Moisture (kg mcwb/yr) (lb mcwb/yr)	X	Ratio Oven-dry Weight to Wet Weight (0.xx)	=	Annual Oven-dry Weight of Husk or Shell (od kg/yr) (od lb/yr)	
(e)	Oven-dry Weight of Husk or Shell (od kg/yr) (od lb/yr)	X	Conversion Unit (od MT/kg) (od t/lb)	=	Oven-dry Weight of Husk or Shell (od MT/yr) (od t/yr)	(4.15)

For step 2, the energy assessment, the equation is

(a)	Annual Oven-dry Weight of Husk or Shell (od MT/yr) (od t/yr)	X	Oven-dry Energy Content (MJ/od MT) (BTU/od t)	=	Annual Husk or Shell Energy Potential (MJ/yr) (BTU/yr)	
(b)	Annual Amount Copra Dried (kg copra/yr) (lb copra/yr)	X	Energy Used in Drying Copra (MJ/kg copra) (BTU/lb copra)	=	Annual Energy Used in Drying Copra (MJ/yr) (BTU/yr)	
(c)	Annual Husk or Shell Energy Potential (MJ/yr) (BTU/yr)	−	Annual Energy Used in Drying Copra (MJ/yr) (BTU/yr)	=	Noncompetitive Husk or Shell Energy (MJ/yr) (BTU/yr)	(4.16)

where c = a − b.

For oils, the single equation is

Palms (#)	X	Nuts per Palm (nuts/palm · yr)	X	Fraction Accessible per Year (0.xx)	X	Volume Oil per Nut (l/nut) (gal/nut)

X	Oil Energy Value (MJ/l) (BTU/gal)	=	Annual Oil Energy Potential (MJ/yr) (BTU/yr)	(4.17)

The following example shows how to successfully use these equations.

Example:

A copra plantation owner wants to use the excess coconut shells from a copra plantation in a steam generator to produce processing heat for drying the copra. The owner knows he has 8,000 palms on his plantation, which produce twenty nuts/tree · year. About 0.70 kg shell at 15 percent mcwb is produced for every kilogram of dry copra and 0.33 kg dry copra is produced per nut. The LHV of the shells is 13.7 MJ/kg at 30 percent mcwb, which is the expected moisture content at burning. About 10 percent of the shells are expected to be lost during collection. The annual energy potential from excess coconut shells is estimated as follows:

Annual Coconut Shell Energy Potential = Trees X Nuts per Tree per Year X Amount of Shell per Nut X Fraction Accessible and Losses X Energy Content
= (8,000 trees) (20 nuts/tree · yr) (0.7 kg shell/kg copra) (0.33 kg copra/nut) (0.90) (13.7 MJ/kg mcwb)
= 460,000 MJ/yr

NONSUSTAINABLE FOREST BIOMASS AND FOREST RESIDUE DATA

Forest residues are currently being used in the Pacific for solid and, to a negligible extent, liquid fuels. Some data on average moisture content, heating values (low and high), and liquid fuel yields (alcohol production) from the Pacific are given in Table 4.2. These data represent averages based on in-field use of the residues.

Some general patterns show up in Table 4.2. First, senile coconut palms have extremely low heating values per unit volume due to their high moisture contents (50 percent in-forest). Despite these low per unit energy values, the large number of senile coconut palms in the Pacific, however, may make this an important short-term energy source (Energy Mission Reports 1982).

In contrast to senile coconut wood, pine wood or bark and all forms of sawmill wastes have much higher LHVs and HHVs per unit. Even in comparison to many tree species (Appendix D), pine and sawmill residues are at the upper end of energy content per unit of resource. Pine wood and bark have high HHVs because of their resin content. As seen for the logging and processing residues, a variety of moisture contents gives a range of LHVs. This range of heat values

Table 4.2. Average Energy Content and Production of Nonsustainable Forest Bio-

	Solid Fuels		
	Wet Basis		
	Moisture Content at LHV	Low Heating Value (LHV)	
Resource	(% mcwb)	(BTU/lb mcwb)	(MJ/kg mcwb)
Overmature forest (nonsustainable)			
Senile coconut palms[a]	56	2,920	6.8
Logging/logging residues			
Pine wood (dry)[b]	12	7,800	18.0
Processing wastes			
Hardwood wastes (aid-dry)[b]	15	6,500	15.1
Sawmill wastes[c]	45	4,350	10.0
Wood/sawdust[d]	50	3,800	8.6
Forest products			
Coconut shells (air-dry)[f]	13	7,700	17.8
Coconut husks (air-dry)[f]	30	5,700	13.2
Coconut palm oil[b]	na	na	na
Nipa palm oil[e]	na	na	na
Sago palm oil[e]	na	na	na
Sago palm plantation[e]	na	na	na

Sources: [a] Energy Mission Reports, Tonga, Appendix 4.1.2 (1982).
[b] Johnston, Ministry of Energy Report, Fiji (1977).
[c] Tatom (1979).
[d] Newcombe (1982).
[e] Newcombe et al. (1980).
[f] Energy Mission Reports, Solomon Islands, Appendix 2 (1982).

shows how it is important to use the correct energy content of the wood or residue for the moisture content as received at the conversion system (e.g., boiler, stove, gasifier, etc.).

The LHVs for coconut husks and shells on a wet basis (13.2 and 17.8 MJ/kg mcwb, respectively) fall in the middle range of values for forest crops and residues. Again, moisture content at the time of burning greatly affects the actual heating values. More detailed data are presented in Table 4.3 on coconut residues. Given the abundance of coconut shells and husks in the Pacific, this resource is probably

mass and Residues

Dry Basis		Liquid Fuels		
High Heating Value (HHV)		Alcohol Production	Energy Content	
(BTU/od lb)	(MJ/od kg)	(l/ha)	(MJ/l)	Country of Data
8,170	19.0	na	na	Tonga
9,030	21.0	na	na	Fiji
7,600	17.6	na	na	Fiji
8,700	20.0	na	na	Papua New Guinea
8,700	20.0	na	na	Solomon Islands
9,000	20.9	na	na	Solomon Islands
8,700	20.0	na	na	Solomon Islands
na	na	na	35.6	Fiji
na	na	5,400	–	Papua New Guinea
na	na	690–4,234	–	Papua New Guinea
na	na	15,300	–	Papua New Guinea

Notes: Conversion factors: 1 J = 9.48×10^{-4} BTUs (Thorndike 1978).
In this and subsequent tables, na = not applicable, – = data not available.

key to small- or medium-scale biomass technologies in the future (Energy Mission Reports 1982).

It is obvious that sawmill or pulp mill residues, particularly pine, are high energy sources per unit of volume. The total volume of such residues may be limited, however. Some are currently being used on-site for fuel or other competing uses that could constrain the supply of sawmill and logging wastes in an area. In contrast, coconut shells or husks may have a larger energy potential in the tropics, with a higher total supply potential than all other residues. However, the dispersed nature of the resource may create collection problems for large cen-

Table 4.3. Average Energy and Moisture Contents for Coconut Residues

Coconut Residues	Weight as % Nut Weight (%)	Component Weight per kg Copra (kg/kg copra)	Ratio Oven-dry Weight per Air-dry Weight (od kg/kg mcwb)	Moisture Content as Received[a] (% mcwb)	Low Heating Value as Received[a] (MJ/kg mcwb)	High Heating Value (MJ/od kg)
Meat/oil	25–33	na[b]	na	na	na	na
Oil	na	0.55	na	na	na	na
Shell	13–15	0.70–1.00	0.62	30	13.7	20.85
Husk	30–37	1.60–2.60	0.62	40	10.9	20.00
Water	23–25	na	na	na	na	na

Sources: Energy Mission Reports, Tonga, Appendix 4.1.2; Vanuatu, Appendix 4.1.1; and Cook Islands, Appendix 4.1.2 (1982).

[a] As received means moisture content of coconut shell or husk right after harvest before air drying or oven drying. Low Heating Value = High Heating Value – 0.0114 (High Heating Value) X (Moisture Content); source: Tillman (1978, p. 78).

[b] On average there is 0.18 kg *dry* copra per nut.

tralized energy systems. Charcoaling shells or using shells for domestic cooking in improved stoves may be alternative uses. Transporting charcoaled husks or shells may present a problem, however, since charcoaled husks or shells tend to break up into thin pieces (fines) if transported long distances

The use of palm oils for liquid fuel production has had mixed results in the Pacific. Oils have a wide range of alcohol production levels depending on oil yields, so the figures in Table 4.2 are suggestive estimates only. For alcohol plants to be economically feasible, large oil plantations are probably needed. While there appears to be significant underproduction of oil from current plantations of Nipa and Sago palms, increasing oil production levels would require new planting programs with higher-yielding species and intensive management. Aggressive programs by governments are necessary to initiate such projects, and these types of programs have historically not succeeded in the Pacific (Newcombe et al. 1980).

In summary, forest residues, particularly for solid fuel use, are a resource that can provide a limited but cheap fuel supply in the Pacific. If large-scale use of sustainable fuels is desired, a government or private company will need to develop plantations or cooperatives to assure an adequate supply. Unless the cost of wood fuel is much less than alternative fuels, large energy systems would need a centralized rather than a decentralized supply system.

Example:

A eucalyptus tree plantation proposed for Hawaii is used here as an example of the financial costs of using a forest resource for energy. Short-rotation tree plantations have received increased attention as a serious, long-run energy source for small- and medium-scale energy uses. However, few ex post facto studies on fuelwood's private costs (let alone social costs) have been made. This section presents data on a proposed eucalyptus tree plantation for the Big Island (Hawaii) in the state of Hawaii. Data come from a workshop by the Hawaii Natural Energy Institute (1982) and a second report by Barbour et al. (1983). The first study was a financial (private cost) and the latter an economic (social cost) analysis.

Some basic assumptions are made for an economic analysis of a eucalyptus tree farm for electricity generation:

- Plantation is on 12,000 acres of Puna Sugar lands, Big Island, Hawaii, with 2,000 acres harvested per year.

- Twenty wet tons/acre · year of eucalyptus chips are produced with 50 percent mcwb as received.
- Two thousand acres are harvested annually after year 7; the next harvests are in years 12 and 17.
- Eucalyptus are coppiced, i.e., limbs sprout from previous cuts, so major planting and establishment costs occur only in year 1.
- HHV is 8,170 BTU/od lb (or 16.3 MMBTU/od t).
- Woodchips will produce electricity for sale to the local power grid.
- Project life is 24 years.

The calculations for the wood resource assessment are

Annual Sustainable Potential = (2,000 acres/yr) (20 t mcwb/acre · yr)
= 40,000 t at 50% mcwb per year

Wood Energy Assessment
LHV = HHV − 0.0114 (HHV) (MC)
= 16.3 − 0.0114 (16.3) (50)
= 7.01 MMBTU/t at 50% mcwb

Annual Wood Energy Potential = (40,000 t mcwb/yr) (7.01 MMBTU/t mcwb)
= 0.28×10^{12} BTU/yr

Table 4.4 shows a financial analysis of the first-year costs, and Table 4.5 gives an average annual cost analysis for the tree farm. Table 4.4 shows that negative net benefits are incurred in year 1 since no trees are harvested and thus no sales begin until year 7. In the average annual cost analysis shown in Table 4.5, these negative net cash flows in the first seven years are balanced by revenues obtained after year 7 and spreading the costs over the project life. Thus, the annual net benefits when just comparing fuel supply savings (not power generation plus fuel savings) are a negative $31,400 per year.

In contrast to the first-year or annual average financial cost analyses, Table 4.6 shows a cash-flow statement for an economic analysis of the tree plantation when revenues from electricity generation are used rather than fuel savings and when labor is shadow priced. Table 4.6 differs from Tables 4.4 and 4.5 by the additional power generation costs (retrofitting and operating a wood or bagasse boiler). In an economic analysis, taxes are not included. Land costs and labor costs are priced at their social values, which are lower here due to unemployment in the area. The economic analysis shows negative net cash flows

Table 4.4. First-Year Average Costs in a Financial Analysis[a] for a Proposed Hawaiian Eucalyptus Tree Farm Excluding Power Generation

Costs and Benefits	$000 in year 1
Costs[b]	
Establishment	
Nursery/seeds	114
Site preparation	94
Planting	185
Weeding	183
Fertilizer	300
Land	429
Residual/labor	869
Total costs	2,174
Benefits (sales year 1)	0
Net benefits (benefits – costs)	–2,174

Source: Adapted from Hawaii Natural Energy Institute, Table 4.6 (1982).

[a] In 1982 US$.

[b] Includes capital costs.

Table 4.5. Annual Average Costs in a Financial Analysis[a] for a Proposed Hawaiian Eucalyptus Tree Farm Excluding Power Generation

Costs and Benefits (24-year project life)	$000 per year[b]
Costs	
Operations and maintenance (O+M)	
Establishment (3 cutting cycles)	51.1
Operating	660.0
Harvesting	1,954.0
Capital	
Capital	612.5
Tax credits (10%)	–61.3
Total cost	3,216.3
Benefits[c]	
Fuel oil savings	3,185.0
Net benefits	–31.3

Source: Adapted from Hawaii Natural Energy Institute, Table 8.5 (1982).

[a] In 1982 US$.

[b] Averages are calculated over the typical cycles for total costs, e.g., establishment = 18 years; operating average from three cycles; harvesting as annual cost in Table 8.5 in source.

[c] Benefits are only fuel costs, not fuel plus capital costs, and are estimated here as input energy equivalent for fuel oil replacement. Assuming: US$1.82/US gal, 5.28×10^6 BTU/bbl, 42 US gal/bbl, 0.126×10^6 BTU/gal, then a 0.28×10^{12} BTU/yr input energy of wood adjusted by 63/80 wood/oil boiler efficiency ratio, gives 0.22×10^{12} BTU/yr fuel oil demand or 1,750,000 gal/yr.

Table 4.6. Economic Discounted Cash-Flow Analysis of a Proposed Hawaiian Eucalyptus Tree Farm with Power Generation Costs[a]

	Inputs								Output		
	Tree Farm				Harvesting		Power Generation				
	Operating Costs									Net Present Value by Year	
Year	Land	Fertilizer	Residual	Establishment	Operating Cost	Capital Expenditure	Operating Cost	Capital Expenditure	Revenue	10%	15%
1	429	300	869	576	na	na	na	na	na	-2,184	-2,184
2	429	390	855	161	na	na	na	na	na	-1,782	-1,699
3	429	390	928	0	na	na	na	na	na	-1,647	-1,498
4	429	390	932	3	na	na	na	na	na	-1,605	-1,392
5	429	390	936	10	na	na	na	na	na	-1,568	-1,297
6	429	390	936	51	na	na	na	na	na	-1,558	-1,229
7	429	390	209	20	1,954	4,840	1,470	5,208	5,239	-6,542	-4,922
8	429	390	165	0	1,954	12	1,470	0	5,239	1,861	1,336
9	429	390	120	0	1,954	12	1,470	0	5,239	1,843	1,261
10	429	390	120	0	1,954	52	1,470	0	5,239	1,758	1,148
11	429	390	120	0	1,954	12	1,470	0	5,239	1,737	1,081
12	429	390	120	30	1,954	4,800	1,470	0	5,239	-1,795	-1,065
13	429	390	120	10	1,954	52	1,470	0	5,239	1,602	907
14	429	390	120	0	1,954	12	1,470	0	5,239	1,589	858
15	429	390	120	0	1,954	12	1,470	0	5,239	1,543	795
16	429	390	120	0	1,954	52	1,470	0	5,239	1,472	723
17	429	390	120	0	1,954	4,800	1,470	0	5,239	-1,529	-716
18	429	390	120	0	1,954	12	1,470	0	5,239	1,412	613

19	367	90	0	0	1,954	0	1,470	0	5,239	1,661	708
20	306	0	0	0	1,954	0	1,470	0	5,239	1,699	690
21	245	0	0	0	1,954	0	1,470	0	5,239	1,683	652
22	184	0	0	0	1,954	0	1,470	0	5,239	1,667	616
23	123	0	0	0	1,954	0	1,470	0	5,239	1,650	582
24	61	0	0	0	1,954	0	1,470	0	5,239	1,637	549
							Discounted net present value:			4,602	-3,486

Sources: Hawaii Natural Energy Institute (1982), and study team calculations by Barbour et al. (1983).

Note: These assumptions are made: Tree harvesting begins in year 7, on a 6-year cutting cycle. Eucalyptus regenerates through coppicing after the first harvest at end of year 6. Output revenue is from fuel oil savings from substituting eucalyptus chips for fuel oil. A 10 or 15 percent discount factor is used in finding the net present values.

[a] In US$000.

for years 1–7 with a 10 percent discount rate, but eventually there is a positive net present value by year 24 ($4,602). The different results in Tables 4.4, 4.5, and 4.6 show how first-year or annual financial as compared to cash-flow economic analyses may lead to different economic conclusions about the success or failure of a project.

Agriculture

Agricultural crops or their residues may also be used as energy resources. In the tropics, agricultural energy crops include sugarcane, cassava (manioc), bamboo cane, corn (maize), and rice. Agricultural crop residues that can be used for fuel are sugarcane bagasse, cassava tops, rice straw, coffee husks, cocoa husks, corn residues, and corn oils. As with forest crops, agricultural energy crops or residues may come from either plantations or small-holder plots. Crops may be grown specifically for energy use, or the residues may be used as byproducts of cash or subsistence crops.

Several factors are important in assessing the feasibility of using agricultural crops or crop residues as fuels. First a reliable, adequate, and year-round supply is needed for most users. Crops or residues need to be burned soon after harvest, converted into liquid or charcoal fuels, or stored. A second factor is that alternative uses for the crop or crop residues may decrease such energy supplies. With crops, the food/fuel tradeoff exists by decreasing either subsistence or domestic food consumption levels and balance of payments from cash crops. Crop residues also may be used for livestock feed, bedding, domestic cooking, or environmental (soil) improvement. On the other hand, use of the crops and crop residues for energy may give another source of income to farmers. Third, another limitation to the use of crops or their residues is dispersion. It may not be economical or an efficient use of labor to collect and transport resources from many small-holder plots to a centralized conversion plant, but on-site charcoal processing, production by cooperatives, or on-site fuel use may be ways to use these resources. Fourth, collection of crops or residues for large-scale energy use may not be socially acceptable. For instance, residue collection may be too labor intensive for small-holders with other labor demands.

Whenever a crop or crop residue is being considered for energy use, social attitudes toward growing, harvesting, and collecting the resource should be examined. It is often best to make residue or crop energy programs from local resources (e.g., rice straw, coffee husks, and cassava) currently being used by the people.

AGRICULTURAL CROP AND CROP RESIDUE EQUATIONS

The following equations give the general calculations for making a resource assessment (step 1) and energy assessment (step 2) for crops. In step 1, area and yields are adjusted for accessibility, soil protection, competing uses, and losses. The annual crop potential is converted to its energy potential in step 2 by using either solid or liquid fuel units. Definitions for the terms and examples are found after the equations.

Crop residue equations are presented directly after crop assessment equations. The resource assessment equation is more complex for crop residues than crops, because residue production is usually reported per unit of crop production. In a residue assessment, the accessible and environmental (soil) protection factors are extremely important since residues often provide important soil nutrients.

For an agricultural crop resource assessment, step 1, the equation is

Area (ha) (acre)	X	Annual Crop Yield per Area at Given Moisture Content (MT od or mcwb/ha · yr) (t od or mcwb/acre · yr)	X	Fraction Accessible (0.xx)	X	Fraction Environmentally Permissible to Remove (0.xx)

−	Annual Competing Uses (MT od or mcwb/yr) (t od or mcwb/yr)	−	Storage, Collection, Transport Losses (MT od or mcwb/yr) (t od or mcwb/yr)	=	Annual Crop Potential (MT od or mcwb/yr) (t od or mcwb/yr)	(4.18)

For **step 2** of the agricultural crop energy assessment, the equation is

Annual Crop Potential (MT od or mcwb/yr) (t od or mcwb/yr)	X	Energy Content at Given Moisture Content (MJ/MT od or mcwb) (BTU/t od or mcwb)	=	Annual Crop Energy Potential (MJ/yr) (BTU/yr)	(4.19)

The analyst should be aware of several terms applicable to crops and residues. **Area** refers to the region or area under energy production. The units are hectares or acres. **Crop yield** refers to the average annual production of the crop per unit area. It is important to have the moisture content for that yield, e.g., moisture content wet basis at harvest, air-dry per yield, or on an oven-dry basis. The units are MT/ha or t/acre per year at a specific moisture content. The local data source is the agriculture ministry or department or the agricultural industry, which would provide annual crop reports.

Accessible is the term referring to the proportion of the crop that is actually accessible for harvest as affected by technical and economic factors. The units are fractions (0.xx) of the total crop yields. The local data sources are the agriculture ministry or department, extension agents, and farmers. **Environmentally permissible** implies that a proportion of the crop cannot be removed without causing environmental degradation. The units are fractions (0.xx) of the total crop yields. The local data sources are the natural resource and agricultural ministries or departments, extension agents, and soil scientists. **Competing uses** must also be considered since the use of crops for energy may directly compete with subsistence or cash crops. These other competing uses, if they have a higher price or are necessary for local consumption, should be subtracted from the crop energy potential. The units to be used are MT (t) per year. The local data sources are the agriculture ministry or department and farm households that can supply annual crop reports and projections of cash and subsistence crops. **Losses** are an important part of the equation because during collection, storage, and transport, a certain proportion of the crop is usually lost. Actual potential must adjust for this loss by subtracting it from the gross annual yield. The units used are MT (t) per year. The local data sources are the agriculture ministry or department, extension agents, and farmers.

Energy content in agricultural crops is affected by the moisture, cellulose, or starch content of the crop. It is important to use the energy content associated with the actual moisture value of the crop before it is burned or fermented. The units to use are MJ/MT (BTU/t) at the given moisture content. The local data source is the energy ministry or department, which may have references on heat values by moisture content.

Example:

An energy ministry is looking into the use of cassava for producing liquid fuel as a substitute for diesel in a small electric generator. In the region, there are about 500 ha of cassava owned by small-scale landholders but also an old copra plantation of 2,000 ha that could be converted after removal of the senile palms. About 30 MT/ha · yr of cassava are expected, with 90 percent accessible for use on the old plantation lands but 50 percent accessible on the small-holder lands. In addition, on the small-holder lands 80 percent of the cassava is used by the family or sold to the market, leaving only 20 percent available for energy production. Annual total losses are expected to be about 10 percent of production on both the small-holder plots and the plantation. The energy content of cassava-based ethanol is about

34 MJ/liter, with about 3 liters ethanol/MT cassava. The energy potential is as follows:

Small-holder lands:

Annual Cassava Potential = Area X Yield X Accessible X Losses X Competing Uses
= (500 ha) (30 MT mcwb/ha · yr) (0.50) (1 − 0.10) (1 − 0.80)
= 1,400 MT mcwb/yr

Cassava Energy Potential from Ethanol = (1,400 MT mcwb/yr) (3 l/MT mcwb) (34 MJ/l)
= 140,000 MJ/yr

Plantation lands:

Annual Cassava Potential = (2,000 ha) (30 MT mcwb/ha · yr) (0.90) (1 − 0.10) (0.0)
= 48,600 MT/yr

Annual Energy Potential = (48,600 MT/yr) (3 l/MT mcwb) (34 MJ/l)
= 4,960,000 MJ/yr
= 5.0 GJ/yr

For step 1, a crop residue resource assessment, the equation is:

Area (ha) (acre) X Annual Crop Yield per Area at Given Moisture Content (MT od or mcwb/ha · yr) (t od or mcwb/acre · yr) X Residue Production per Crop Yield at Given Moisture Content (MT od or mcwb/MT od or mcwb) (t od or mcwb/t od or mcwb)

X Fraction Recoverable (0.xx) X Fraction Environmentally Permissible (0.xx) − Annual Competing Uses (MT od or mcwb/yr) (t od or mcwb/yr)

− Storage, Collection, Transport Losses (MT od or mcwb/yr) (t od or mcwb/yr) = Annual Crop Residue Potential (MT od or mcwb/yr) (t od or mcwb/yr) (4.20)

For **step 2**, the crop residue energy assessment, the equation is

Annual Crop Residue Potential at Given Moisture Content (MT od or mcwb/yr) (t od or mcwb/yr)	X	Energy Content at Given Moisture Content (MJ/MT od or mcwb) (BTU/t od or mcwb)	=	Annual Crop Residue Energy Potential (MJ/yr) (BTU/yr)	(4.21)

It is important that the energy analyst be aware of several definitions related to crop residue assessments. **Area** is the region or area considered for energy production. The units are hectares or acres. **Crop yield** refers to the average annual yield per unit area for the primary crop whose residue is being used. The units are MT/ha or t/acre per year. The local data sources are the agriculture ministry or the department, annual crop reports, and farmers. **Residue yields** may be either given as a ratio of the volume of residue per volume crop (MT or t residue/MT or t crop) or as volume (MT or t residue) per ha or acre. If residue yields are reported in terms of crop yields, then both crop yields and a residue : crop ratio must be used as in the above equation. If residue yields are already expressed on a per area basis, e.g., MT mcwb/ha, however, then a residue : crop ratio does not need to be used in Equation 4.21. For a ratio, the units are MT (t) of residues per MT (t) of crop. The local data sources are the agriculture ministry or department, extension agents, and farmers.

The term **recoverable** reflects the fact that crop residues are waste products of agricultural production, hence residue collection may not be a high priority of farmers. As residue collection is labor-intensive, all the potential residue may also never be recovered. Thus, a "recoverability" factor is needed to provide a realistic estimate of the residue collection expected by farmers. If residues come from crops such as sugarcane bagasse and coffee husks that are brought to a centralized processing area, more residues may be recovered than if residues are left in the field and a second harvest is necessary. The units are fractions (0.xx) of the total gross yields. The local data sources are the agriculture ministry or department and local agro-industry personnel such as extension agents, farmers, agronomists, and operators of crop-processing facilities or storage warehouses. **Environmentally permissible** reflects the practice of leaving residues on the ground after harvest to replace soil nutrients. Besides adding to the soil's mineral and organic content, residues may also protect the soils from wind and water erosion. In the tropics where soils are particularly susceptible to heat exposure and nutrient losses, a soil protection factor is extremely important to keeping long-term agricultural productivity high. The units are fractions (0.xx) of the total gross yields. The local data sources are the agriculture ministry or department, agronomists, soil scientists, and farmers.

Competing uses means that alternative uses—such as domestic cooking, mulching, animal feed, or bedding—may already exist for crop residues. If such end uses provide better uses to society or if they draw higher prices than residue use as energy fuels, these competing uses should be subtracted from the gross potential.* The units are in MT(t) per year. The local data sources are the agriculture ministry or department, crop reports, extension agents, and farmers.

Losses is a term that reflects the crop residue lost to pests and handling problems during collection, storage, and transport. The units to be used are MT (t) per year. The local data sources are the agriculture ministry or department, extension agents, farmers, and crop storage facility operators.

Energy content of crop residues depends upon the moisture content and the amount of cellulosic or sugar material in the residue. As with forestry and agricultural crops, the LHV of residues must be given for that specific moisture content since oven-dry residues are never used. The units are MJ/MT or BTU/t on an oven-dry or wet basis or MJ/liter or BTU/gal. The local data sources are the energy ministry or department and the engineering departments where experiment station data may be found.

Example:

Sludge from a palm oil mill is proposed to be used in a biogas digestor (Energy Mission Reports, Solomon Islands, 1982). About 300 kg of sludge is produced per MT of fresh fruit bunches, and 85,000 MT of palm oil fruit bunches are processed per year. The biogas production is assumed to be 28.3 m^3 gas/m^3 sludge. Adapting data from the report, the physical and energy assessment calculations are as follows:

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* Over time, if changes occur in the comparative advantages of using the residues for energy versus feed or alternative uses, then these alternative uses may be added into the potential. Often, it is helpful to provide policy makers with a low estimate (competing uses subtracted out of the total) and a high estimate (competing uses included in the total).

Table 4.7. Average Energy Content and Production for Crops and Crop Residues in

	Solid Fuel			Liquid Fuel	
	Moisture Content at mcwb	LHV at mcwb		Average Production	Fermentables
Biomass Feedstock	(%)	(BTU/lb)	(MJ/kg)	(MT/ha · yr)	(%)
Crops					
Bamboo cane[a]	10	7,400	17.2	na	na
Cassava (manioc)[b]	na	na	na	30	30
Corn (maize)[c]	na	na	na	25–40	25–30
Sugarcane[a]	12	7,500	17.3	na	na
Crop residues					
Bagasse (sugarcane)[a]	12	7,300	16.8	na	na
	50	4,000	9.2	na	na
Cassava tops[a]	51	5,600	13.0	na	na
Coffee husks[a]	30	6,000	14.0	na	na
Rice hulls[a]	40	6,400	15.0	na	na
Oils/wastes					
Coconut oil[b]	na	na	na	na	na
Corn oil[b]	na	na	na	na	na
Nipa palm oil[d]	na	na	na	na	na
Palm sludge oil[e]	na	na	na	na	na
Sago palm oil[f]	na	na	na	na	na
Sunflower oil[b]	na	na	na	na	na

Sources:
a Johnston (1976).
b McCann and Associates (1980).
c Solly (1981).
d Newcombe et al. (1980).
e Energy Mission Reports, Solomon Islands (1982).
f Flach (1981).

Annual Palm Oil Sludge Potential = (300 kg/MT fruit) (85,000 MT/yr fruit)

= 25,500,000 kg/yr

= 25,500 m^3/yr

Palm Oil Energy Potential = (25,500 m^3/yr) (28.3 m^3/m^3 sludge)

= 722,000 m^3 gas/yr

the Pacific

		Gaseous Fuel		
Starch Content (kg dry starch/kg)	Energy Content (MJ/l)	Average Production (kg/MT)	Energy Production (m^{3}gas/m^3)	Country of Data
na	na	na	na	Fiji
na	na	na	na	Fiji
na	na	na	na	Papua New Guinea
na	na	na	na	Fiji
na	na	na	na	Fiji
na	na	na	na	Fiji
na	na	na	na	Papua New Guinea
na	na	na	na	Papua New Guinea
na	na	na	na	Papua New Guinea
–	35.6	na	na	Fiji
–	36.0	na	na	United States
120	18/kg sugar	na	na	Papua New Guinea
–	–	250–325	28.3	Solomon Islands
154–185	–	na	na	Papua New Guinea
na	36.0	na	na	Fiji

AGRICULTURAL CROPS AND CROP RESIDUE DATA

Given the varied agricultural base of the tropics, many crops and residues could be used for energy production. The desired energy use (e.g., liquid, solid, or gaseous fuel) often determines the crop that should be used as a feedstock. For example, if alcohol is the desired end product then crops or crop residues such as sugarcane bagasse or palm oil with high sugar levels are used. If solid fuels are needed for burning, then a crop such as husks or bagasse with a high lignin content is needed. Table 4.7 lists some possible crop and crop residue fuels that could be used in the tropics. The data come from a variety of Pacific sources and represent average production levels for these crops and crop residues under normal field conditions. Table 4.7 is divided into solid or liquid fuel production. The energy contents for crops and crop residues at the reported moisture contents are similar to the LHVs of solid forest fuels found in Tables 4.1 and 4.2. Bagasse, coffee husks, and rice hulls are already being used or proposed for use by processing facilities in the tropics (Newcombe 1982, Johnston 1976). The use of oils for alcohol production has only recently been explored and has produced mixed results due to technical but mostly financial problems (Newcombe et al. 1980). The production and energy figures in Table 4.7 for liquid fuel production are only approximate values given the limited database and could be much higher if proper management existed.

In summary, crops often have higher demand as food or cash crops than as energy crops. As a consequence, production as energy crops will probably be limited to plantations. When used, crops for liquid fuel production are the most attractive option, but again a food-fuel competition exists, and the high costs of financing alcohol plants has constrained commercial projects in the Pacific islands (Newcombe et al. 1980). In contrast, crop residues probably hold the greatest promise in the future but they, like forest residues, have supply limits and must be managed wisely to prevent soil nutrient problems.

Animal or Solid Wastes

Waste materials from animals, industries, or households may be used for energy. Liquid waste material such as human or animal feces or agricultural wastes (sludge) are often used in biogas digestors to produce gaseous fuels. Nonliquid burnable materials such as paper products and trash can be burned in solid waste boilers. However, given the larger amount of animal and human wastes relative to solid wastes in the Pacific islands, this section examines only liquid waste materials.

Energy production from liquid wastes generally has been quite low in the Pacific, due partly to overestimating the available as compared to realistic waste supply for biogas digestors, the main technology using these wastes. Both the amount of available waste and the concentration per unit area affect the actual supply. Data on waste material per animal or human are often calculated in production yields under confined or centralized conditions, as is the case in many Western countries. These conditions may not exist in some rural areas in the Pacific. Thus, traditional livestock and human refuse disposal patterns and social attitudes toward collecting and confining waste materials may decrease original supply estimates. Further, more important reasons for the lack of successful digestors are social acceptability and technical problems. Sometimes they simply have not worked. This section looks at supply estimation rather than technical or social feasibility.

ANIMAL OR SOLID WASTE EQUATIONS

The equations for calculating energy potential from different waste materials are given below. In general, daily or weekly production rates should be converted into annual potential and adjusted for realistic collection possibilities or competing uses. With regard to animal or human wastes, the percentage that is *actually* collectible is important. Competing uses for energy fuels such as cow dung and pig manure may also significantly affect the actual annual potential available for energy production. Information on the collectible percentage and competing uses will most likely come from farmers or rural households. Surveys to obtain average yields may be the best data sources (Siwatibau 1981). The general equations below can be used for human, livestock, and agricultural wastes.

For **step** 1, the resource assessment, the equation is

Daily Waste Production per Unit (kg/head · day) (lb/head ·day)	X	# Units (heads)	X	Average Days of Production per Year (days)

X	Fraction Collectible (0.xx)	–	Annual Competing Uses (kg/yr) (lb/yr)	=	Annual Waste Potential (kg/yr) (lb/yr)	(4.22)

For **step** 2, energy assessment, the equation is

Annual Waste Potential (kg/yr) (lb/yr)	X	Unit Conversion Factor (MT/kg) (t/lb)	X	Gas Production per Unit Waste Material (m^3/MT) (ft^3/t)

X	Energy Content of Gas Material (MJ/m^3) (BTU/ft^3)	=	Annual Waste Energy Potential (MJ/yr) (BTU/yr)	(4.23)

In the above equations, it is assumed that biogas is produced from these wastes. For this reason, energy content is expressed in megajoules (or BTUs) per cubic meter (or cubic foot) of gas production. If waste materials are burned rather than gasified, conversion to gaseous units is unnecessary, but air-dried data must be used.

Several definitions are applicable to the animal/solid wastes assessment. **Daily waste production** refers to the average daily amount of waste that could be expected from the animal, agricultural effluence, human, or other waste unit, e.g., head of cattle, pigs, or per person. This production rate should reflect actual confinement or collection conditions that prevail in the area. If production data come from other areas then the data may need to be raised or lowered accordingly. Local extension workers and farmers should be able to provide the analyst with this information. The units are kilograms or pounds per unit per day for solid wastes or liters or gallons per unit per day for liquid wastes. The local data sources are the agriculture ministry or departments and the livestock industries, which include animal scientists, extension workers, and farmers.

The **number of units** refers to the number of livestock (cows, pigs, chickens) or humans or the amount of industrial effluence. It is critical to use the correct data with liveweight of animals in the region. The units are measured in number (#). The local data sources are the census bureau and the agriculture ministry or department, which provide population and livestock statistics or industrial surveys. **Days of yearly production** represents a realistic number of production days needed to estimate annual potential. The daily production rate is adjusted for seasonal fluctuations if necessary. The units to be used are days per year. The local data sources are the agriculture ministry, extension agents, livestock managers, farmers, households, and public works officials.

Collectible factor is a term used if the daily waste production value does not reflect the collectible proportion (i.e., the actual amount available). This factor is particularly important for unpenned animals or when negative social attitudes about feces collection exist. The units are fractions (0.xx) of the total production. The local data sources are the agriculture ministry or department, sociologists, farmers, extension workers, and rural households. **Competing uses** for waste material include fertilizer, on-site fuel use, or animal feed. The units involved are kilograms or pounds per year for solid waste material and liters or gallons per year for liquids. The local data sources are the agriculture ministry or department, the public works ministry, farmers, households, and extension workers. **Unit conversion factor** refers to the conversion of kilograms (pounds) into metric tons (tons); most gas production data are reported in tons.

Example:

A farmer with a pigsty (10 pigs) is considering installing a biogas digestor to produce gas for domestic cooking and lighting in several buildings. He or she wants to know the energy potential from the pigsty. Assuming the pigs each weigh 100 pounds, the farmer can expect 2.5 ft^3 of gas per day from a 100-pound pig. The annual gas production is estimated as follows:

Annual Biogas Production = (10 pigs at 100 lbs each) (2.5 ft^3/day · 100-lb pig) (365 days/yr)
= 9,100 ft^3 gas/yr

Annual Energy Production = (9,100 ft^3 gas/yr) (331 BTU/ft^3)
= 3.0×10^6 BTU/yr

ANIMAL OR SOLID WASTE DATA

Much of the biogas production research comes from developed countries, so such data may often need revision to reflect local conditions. Tables 4.8, 4.9, and 4.10 present data from many areas. Technical improvements in digestors may have increased laboratory yields, but in-field use would tend to lower the gas yields reported in the tables. These two effects may offset each other. In Table 4.8, gas production goes from 69 ft^3 per day for dairy cows to 0.25 ft^3 per day for broiler hens (Siwatibau 1981). Digestor gas, typically, has 22.0 MJ/m^3 (LHV) or 331 BTU/ft^3.

Table 4.10 gives gas production in m^3/kg of dry matter; the table is adapted from Van Brakel's 1980 review of small-scale anaerobic digestors and usually represents laboratory rather than in-field data. An average production for organic wastes is in the range of 0.01–0.09 m^3/kg of dry matter; sewage and garbage production appears to have a similar range (0.07–0.10 m^3/kg of dry matter), and animal manures have a smaller gas production range of 0.02–0.035 m^3/kg of dry matter. Such variation is small and really insignificant. Any biogas analysis should include more accurate data from local or regional data sources.

Charcoal

In the Pacific, charcoal is made from wood, coconut husks or shells, and lumber wastes. In this section, charcoal's energy or fuel

Table 4.8. Average Biogas Production

Animal	Liveweight (pounds)	Biogas (ft^3/day)
Dairy cow	1,600	69
Dairy heifer	1,000	37
Beef heifer	1,000	29
Beef stocker	500	20
Hog	500	8
Hog	200	5
Hog	100	2.5
Piglet	15	0.37
Hen (broiler)	4	0.25
Hen (laying)	4	0.20
Human (including urine)	150	1.25

Sources: Figures are extracted from Siwatibau (1981) and Merrill and Gage (1978).

Note: See Appendix E for additional detailed data.

Table 4.9. Average Domestic Biogas Consumption[a]

Use	Conditions	Consumption
Cooking	2-in-ring burner	11.5 ft^3/hr
	4-in-ring burner	16.5 ft^3/hr
	6-in-ring burner	22.5 ft^3/hr
	Person per day	12–15 ft^3
	Family of 4–6 per day	49–72 ft^3
Lighting	1 mantle	3 ft^3/hr
	2 mantles	5 ft^3/hr
	3 mantles	7 ft^3/hr
Refrigeration	1 ft^3	1.2 ft^3/hr

Sources: Figures are extracted from Siwatibau (1981) and Merrill and Gage (1978).

[a] The table provides very rough guidelines to the gas consumption one might expect in actual field conditions in the Pacific islands based on 5 ft^3 of gas per pound of volatile solids and consumption at 2–3 inches of water pressure (1 atmosphere = 33.9 feet of water). One imperial gallon of petrol is equivalent to about 250 ft^3 of biogas and 100 ft^3 of biogas and 100 ft^3 of volume = 2.8 m^3 = 625 imperial gallons. A small (1–10 British horsepower) petrol engine will consume about 16 ft^3 of biogas per hour per rated horsepower or 19 ft^3 of gas/hr/actual horsepower (due to power loss when using biogas); 1 kWh of electricity will require 50–60 ft^3 of gas at 2–4 inches of water pressure.

Table 4.10. Average Biogas Production from Various Waste Materials

Waste, Country	(m^3/kg)
Cow dung	
India	0.30
India	0.10–0.30
India	0.23–0.50
Cow manure[a]	
Germany	0.23–0.27
France	0.20–0.35
USSR	0.18–0.23
USA	0.16–0.19
Israel	0.09
Swine dung	
Germany	0.26–0.39
Swine manure	
USSR	0.20
Taiwan	0.24
Horse manure	
USSR	0.18
Sheep manure	
USA	0.12–0.32
Paper[b]	
newspaper	0.30
mixed paper	0.23
Other wastes[b]	
cotton, textile	0.28
vegetable wastes	0.44–0.60
organic refuse	0.26
grass	0.22–0.49
leaves	0.10–0.30
seeds	0.02–0.43
night soil	0.40–0.70
sewage screenings	0.31–0.37
Sewage[c]	
sewage sludge	0.10–0.60
sewage sludge + garbage	0.10–0.90
garbage	0.30–0.70
sewage sludge + garbage – paper	0.20–0.50
sewage sludge + industrial wastes	0.10–0.60
leaves	0.32

Source: Adapted from Van Brakel, Tables 2.1 and 4.1 (1980).

[a] Manure is a dung-straw mixture.

[b] From laboratory data for batch experiments with a duration of 30–70 days.

[c] From data for large-scale digestor tanks at sewage works.

characteristics are discussed, but the charcoal production process is discussed in Chapter 5.

Carbonization is an old technology to produce charcoal, i.e., compacted carbon. The use of charcoal has many advantages. In terms of its density and transportability, charcoal is denser per ton than wood fuels. This means charcoal's transport costs are lower per unit of volume than are the costs for fuelwood. However, if transported long distances, charcoal may break into small pieces (fines) and require briquetting. Charcoal has a wide range of production since it can be produced by small and large landholders. Charcoal is also a high-quality fuel. Because of uniform size and density, charcoal evenly radiates heat, an advantage for cooking and industrial uses. In industrial use, it can be mixed with or substituted for fossil fuels such as coal or fuel oil in boilers. Since charcoal is mostly carbon, it produces different types of pollution than wood fuels. Charcoal also is extremely low in sulfur and produces few tars (Hyman 1981). In addition to a range of domestic, industrial, and commercial energy uses, charcoal could be exported if such a market exists. However, past experience in the Pacific has not been favorable for exports due to poor product quality and limited markets.

Charcoal use, however, does have some critical limitations. First, from 30 to 85 percent of the original energy content in wood fuels is lost during charcoal production. This loss due to conversion reduces the total efficiency of converting charcoal to energy (Hyman 1981). Charcoal's quality as a fuel, secondly, depends upon the type of fuel used in carbonization. Wood fuels with high moisture content, low density, and fines produce poor-quality charcoal that is only good for domestic use. Good sources for charcoal production are coconut shells (not coconut wood or husks), dense hardwoods, and solid lumber wastes (not sawdust) (Energy Mission Reports 1982). Finally, if wood species or residues are used for charcoal production, and more wood is needed to produce the same amount of usable (output) energy with charcoal than if the wood was directly burned, environmental damage from deforestation and soil erosion may actually increase.

In summary, high-quality charcoal is a preferred fuel over wood for both industrial and domestic users because of its quality and ease of storage and transport. But charcoal use may have critical energy inefficiencies and environmental problems. Its major potential in the Pacific will be for domestic cooking in urban or urban fringe areas. An urban market would give rural charcoal producers cash income and would increase urban-rural sector links. If high-quality charcoal is briquetted, the product could be more easily transported and exported to close foreign markets.

CHARCOAL EQUATIONS

Charcoal energy potential is estimated in step 1 by determining the amount of charcoal produced from a given amount of wood or wood residue. In step 2, the charcoal potential is multiplied by the energy content per unit of charcoal. The energy content must be adjusted by the moisture content of the charcoal (e.g., LHVs) and ultimately by the conversion efficiency of the end-use process, as discussed later in Chapter 5.

In **step 1**, charcoal resource assessment, the equation is:

Annual Wood or Wood Residue Volume (MT od or mcwb/yr) (t od or mcwb/yr)	X	Charcoal Production per Mass Wood (MT/MT) (t/t)	−	Annual Losses (MT od or mcwb/yr) (t od or mcwb/yr)	
− Competing Uses (MT od or mcwb/yr) (t od or mcwb/yr)	=	Annual Charcoal Potential (MT od or mcwb/yr) (t od or mcwb/yr)			(4.24)

For **step 2**, energy assessment, the equation is:

Annual Charcoal Potential (MT od or mcwb/yr) (t od or mcwb/yr)	X	Energy Content at Given Moisture Content (MJ/MT od or mcwb) (BTU/t od or mcwb)	=	Annual Charcoal Energy Potential (MJ/yr) (BTU/yr)	(4.25)

Example:

A copra plantation owner wants to use his excess coconut shells for charcoal production. He produces 3 MT of shells (30 percent mcwb) per week from his land with a charcoal conversion efficiency of 20 percent going from the shells to charcoal. However, about 10 percent of the shells are lost during collection and storage, 30 percent of these shells are already being used to dry copra, and the plantation operates 50 weeks per year. The average energy potential of charcoal is 29 MJ/kg at 5 percent mcwb. The calculations to determine the resource assessment are:

Annual Charcoal Potential = (3 MT mcwb/wk) (50 wk/yr) (0.20) (0.90) (0.70)
= 19.0 MT mcwb/yr
= 19,000 kg mcwb/yr

To determine annual charcoal energy potential, the calculations are:

Annual Charcoal Energy Potential = (19,000 kg mcwb/yr) (29 MJ/kg at 5% mcwb)
= 550,000 MJ/yr

CHARCOAL DATA

Characteristics of the wood used to make charcoal are important to charcoal quality. Wood fuels with low commercial value, such as stems, branches, low-quality timber, or residues are often used for charcoal production. Charcoal quality also depends upon its mixture of fixed carbon, volatiles, ash, and moisture (Hyman 1981, Newcombe 1981). As there is often only a small difference in energy content between charcoal produced from different types of woods, low-quality wood resources should be used for charcoal production. Charcoal's energy content varies according to its moisture content, length of storage, and density, but average energy values used in the Energy Mission Reports (1982) for charcoal produced in Western Samoa and Fiji range from 29–32.6 MJ/kg (12,900–14,000 BTU/lb). The average moisture content for charcoal is 2–5 percent coming out of the kiln but is higher if made in earth-mounded kilns (Hyman 1981). Moisture content may rise to more than 10 percent after storage and air exposure. In the tropics, proper storage is necessary to ensure higher combustion efficiencies for charcoal. In contrast to wood, charcoal does not deteriorate while in storage.

Some good charcoal feedstocks include *leucaena leucocephala* (ipil-ipil) and coconut shells. Unless briquetted, coconut logs form low-density, poor-quality charcoal with fines, which makes them crumble when transported (Hyman 1981, Newcombe 1984). Coconut shells are generally good feedstocks since they produce a uniform charcoal with few impurities but may also produce fines if not properly managed. Logging and lumber wastes can also be made into charcoal, but they tend to produce charcoal with lower heating values than denser woody materials (Hyman 1981). Sawdust is not a good feedstock because its low density prolongs the production process (Hyman 1981).

SOLAR RESOURCE ASSESSMENT

In the tropics, the primary uses of solar energy seem to be heating water and generating low-power electricity using photovoltaics for communications, lighting, and pumping water. Solar collectors are useful for heating water for homes, hotels, and industries. Solar-powered refrigeration is now technically reasonable but only sometimes cost-effective. Other uses, such as space heating, air conditioning, and multi-kilowatt electrical generation, are technically possible but in the tropics are either unnecessary or too expensive to be generally useful.

Before presenting solar energy equations, common definitions used in solar energy assessment are needed. **Solar radiation** is the technical term for the sun's energy and consists of heat (infrared radiative energy), visible light, and a small amount of ultraviolet radiation, which provides little useful energy but causes sunburn, fading of paint, and deterioration of plastics. In terms of energy, the infrared part, which is invisible, is about as strong as the visible part, so the eye is not a reliable instrument for estimating solar energy. The value of **extraterrestrial radiation**, radiation at earth's outer atmosphere, is used as a standard to estimate the effects of clouds, dust, and air on solar radiation at ground level. The solar energy we see is far from constant but measurements taken in outer space, away from the clouds, dust, and air of the atmosphere, show that there is little change in the sun itself. This value is primarily of interest only to those working in outer space.

Horizontal radiation is the quantity of solar radiation falling on a flat, level surface. Most solar radiation measurements that are made by weather services are of this type and are considered a reasonable estimate of the solar energy on the ground. **Tilted surface radiation** is solar energy falling on a surface that is not horizontal. Since most solar energy devices are not mounted level, tilted surface radiation is a more appropriate measurement of solar energy. Note, however, that the actual amount of energy received changes with the tilt angle; therefore, tilted surface radiation measurements must be taken with an instrument tilted at the same angle as the solar unit or corrections must be made to the data. Very few long-term measurements are made with tilted instruments; usually tilted-instrument measurements are taken only in conjunction with an operating solar installation.

Solar radiation can be broken into three components. **Direct** or **beam radiation** is that radiative energy coming only from the sun. Very few places have solar instruments that actually track the sun's movement and constantly measure the energy available directly from it. The instruments that do so—called pyroheliometers—see only the sun itself by blocking out the sky and all its surroundings. **Indirect** or

diffuse radiation is the radiation coming from the sky and surroundings but not directly from the sun. Note that when the sun is behind a cloud, all solar radiation falling on the ground is diffuse, while on very clear days less than 10 percent may be diffused with more than 90 percent as direct radiation. As a rule, shadows are caused by direct radiation; the darker the shadow, the greater the amount of direct radiation there is in relation to diffuse. **Reflected radiation** is the radiation reflected from surrounding surfaces that falls on the solar unit. **Albedo** is a number between 0 and 1 signifying the fraction of sunlight that is reflected by a surface. White sand has a high albedo, often above 0.8, while dark soil may have an albedo of less than 0.2. **Total radiation** is the sum of diffuse, reflected, and direct radiation. Sometimes called **global radiation**, for practical purposes it is the same as horizontal radiation if the receiving unit is mounted horizontally or the same as tilted surface radiation when the receiving unit is tilted.

As discussed later, solar radiation is often estimated by using various proxies. **Percent cloudiness** is a number between 0 and 100 that is the observer's estimate of the percentage of the sky that is covered with clouds. Note that the estimate is not an instrument measurement and its accuracy is dependent upon the experience and ability of the observer. Further, even if the observer accurately estimates the percentage of cloud cover, it is not necessarily true that clouds cover the sun. **Sunshine hours** refers to a measurement of the number of hours per day that the sun shines brightly, with direct radiation significantly exceeding diffuse radiation. The measurement is usually taken by either a Campbell-Stokes Sunshine Meter or a Sunshine Switch. The Campbell-Stokes unit is simply a glass ball that acts as a lens and causes strong sunlight to burn a trail on a piece of record paper. The record is then examined and the measurement of the burned strip is converted into sunshine hours. The Sunshine Switch is an instrument that senses bright sunshine by closing an electrical circuit. The switch usually gives sunshine hours directly.

The Meaning and Use of Solar Measurements

Three types of solar records exist for the Pacific region: (1) global radiation measurements taken with good-quality, automatic instruments called pyranometers; (2) sunshine hour data usually collected with Campbell-Stokes instruments; and (3) cloudiness estimates provided by observers. Global maps of solar radiation, a fourth source, are simply too general and misleading for most Pacific island countries where climates are highly variable. While very few sites use pyranometers, most measure sunshine hours as part of the regular meteorological data service. Unfortunately, none of these data sources proves very useful except in a limited sense for estimating the size of solar units for solar energy installations. Some suggest that cloud cover data can be used to estimate solar energy, but their accuracy is much in doubt (Droz 1985) and so far remains inappropriate for use in tropical island countries. With the exception of a few sites, such as Nadi, Fiji, long-term, high-quality solar data are insufficient to allow useful calculations of solar system size based on energy input.

First of all, solar radiation is notoriously variable from year to year, thus it takes many years of data collection to determine the minimum and maximum solar energy that can be expected at a given site. Few places in the Pacific have recorded solar data long enough to establish this range with any accuracy. Secondly, the mountainous Pacific island countries have large site variations of solar radiation due to local clouds caused by mountains. For that reason, measurements taken at one site are not usable at another just a few kilometers away. Thirdly, we need energy information, not sunshine-hour information, and although formulas exist for estimating energy from sunshine hours, the accuracy of such estimates is questionable for tropical islands. Finally, cloudiness estimates are poorly related to solar energy compared with sunshine hours and are therefore even less useful for our purposes. Given no other information, however, sunshine hours and cloudiness data can be used as second-best options in formulas reported later.

PYRANOMETER DATA: DIRECT MEASUREMENT METHOD

With at least five years of high-quality solar radiation data, useful engineering calculations can be made to help determine solar system size. Such calculations are best accomplished by using computer programs such as F-CHART and should be included in any high-cost solar project to be built at a site where several years of solar data are available. Such detailed calculations are usually left to design engineers from engineering firms, aid agencies, and solar unit manufacturers. The calculations made are very site- and system-specific. The calculations include solar data considerations, collection device efficiency, storage and delivery system losses, and energy use patterns. Because several ways exist to make these calculations and very few experienced solar engineers are available, a second opinion is recommended for sizing particularly expensive or marginally economic systems.

For planning purposes, extended calculations have little value since they are so site-specific. The best use of the data is site categorization.

With accurate data available, more categories can be reasonably defined. To categorize, however, the measurement units must first be determined. Data have been recorded in Langleys (gram calorie per square centimeter: cal/cm^2), watts per square meter (W/m^2), British thermal units per square foot (BTU/ft^2), and megajoules per square meter (MJ/m^2). Each can be converted to the other (sometimes with a unit of time required) as shown below. For the Pacific, the Langley continues to be the common unit found in records of pyranometer data. The conversions are:

1 Ly = 11.63 Wh/m^2
1 BTU/ft^2 = 3.154 Wh/m^2
1 BTU/ft^2 = .2713 Ly
1 MJ/m^2 = 88.1 BTU/ft^2

The suggested divisions are: *excellent,* where the yearly average is equal to or greater than 600 Ly per day; *good,* with a daily average equal to or greater than 500 but less than 600 Ly/day; *satisfactory,* where the daily average is equal to or greater than 400 but less than 500 Ly/day; *fair,* where the daily average is equal to or greater than 300 but less than 400 Ly/day; and *poor,* with a daily average of less than 300 Ly/day.

These dividing lines are arbitrary and are intended to be used for guidance in categorizing sites but not for predetermining system performance.

SUNSHINE HOUR, CLOUD COVER, AND RAINFALL METHODS

Although sunshine hour, cloudiness, and rainfall data are not satisfactory for directly estimating energy inputs to a solar system, these data are useful for categorizing solar sites. Three categories–good, satisfactory, and fair–are suggested on the basis of existing data. Certainly excellent and poor sites are found in the Pacific, but with very few exceptions it is unreasonable to make site determinations based solely on available sunshine hour and cloudiness data.

A *good* rating is assigned to a site with an average of 5 or more sunshine hours a day or an average cloudiness level of 25 percent or less. The *satisfactory* rating is assigned to sites with an average of 3 to 5 sunshine hours per day or average cloudiness percentages from 25 to 60 percent. Sites with less than an average of 3 sunshine hours per day or more than an average of 60 percent cloudiness are considered *fair* to *poor.*

If precise recordings for a potential site are unavailable or inappropriate or these simple rules of thumb are not sufficient, the average monthly surface radiation (energy) can be statistically correlated with sunshine hours, cloud cover, or rainfall. The following theoretical methods can be used for estimating the average solar radiation. The methods are based on clear day or extraterrestrial radiation (the clearness index), cloud data, and rainfall data. To fully understand the mathematics and work with examples, analysts can refer to Kreith and Kreider (1978), Twiddell and Weir (1985), and Duffie and Beckman (1980). Droz (1985) uses empirical data from Fiji and Hawaii to demonstrate the reliability and accuracy of these estimation techniques. These techniques, however, may not be more accurate than using the simple rules of thumb listed above.

Sunshine Hour or Clear Sky Method. Surface radiation is often estimated by examining the empirical relationship between radiation (energy) and sunshine hours or average percent of possible sunshine (PPS) hours. As described earlier, these data often can be obtained from weather stations. The relationship below equates monthly average daily radiation hitting a horizontal surface ($\overline{H}$) to clear day radiation ($\overline{H}_C$) and average fraction of possible sunshine hours ($\overline{n}/\overline{N}$) as given by Duffie and Beckman (1980):

$$\overline{H}/\overline{H}_C = a' + b'(\overline{n}/\overline{N})$$

where $\overline{H}$ = monthly average daily radiation on a horizontal surface

$\overline{H}_C$ = average clear day daily radiation for the site during that month

$\overline{n}$ = average daily hours of bright sun in that month

$\overline{N}$ = average of daily maximum possible hours of bright sunshine for that month (the length of the average day in the month)

a', b' = constants, estimated in the regression equation

The empirical constants a' and b' for Nadi, Fiji, are calculated from a regression equation (Droz 1985). The difficulty with this equation is measuring the average clear sky radiation ($\overline{H}_C$) and $\overline{n}/\overline{N}$ since the clear sky measure is completely subjective. The $\overline{n}/\overline{N}$, also called the percent of possible sunshine (PPS), is likewise difficult to measure accurately. Using the above equation, solar radiation is found as:

$$\overline{H} = \overline{H}_C\,[a' + b'(\overline{n}/\overline{N})]$$

Because of the problems in defining clear day, Page redefined

Angstrom's sunshine-based equation using extraterrestrial radiation ($\bar{H}_O$) rather than clear day radiation ($\bar{H}_C$) since data on $\bar{H}_O$ for any particular site can be obtained easily from global solar maps (Duffie and Beckman 1980). The equation for the Angstrom-Page regression equation is written as follows:

$$\bar{H} = \bar{H}_O \left[a + b(\bar{n}/\bar{N})\right]$$

where

$\bar{H}_O$ = average extraterrestrial radiation for a given latitude in that month

a, b = empirical constants

Again, $\bar{H}$ is the average horizontal surface radiation (energy) for a given month. Compared with clear day radiation, the use of extraterrestrial solar radiation ($\bar{H}_O$) gives a better statistical relationship to surface radiation ($\bar{H}$), according to Kreith and Kreider (1978). The ratio of average daily solar radiation on a horizontal surface to average extraterrestrial solar radiation is called the **clearness index** (K_T):

$$K_T = \bar{H}/\bar{H}_O$$

where K_T = clearness index

This constant, K_T, is used in many solar engineering equations. Optimally a, b, and $\bar{H}_O$ should be known for a given site but in lieu of such data, data on a and b from similar climate types could be used (as in Droz 1985).

Cloud Cover Method. If data on sunshine hours are not available but information on the mean monthly cloud cover exists for a potential site, the relationship between average daily radiation ($\bar{H}$) to monthly cloud cover ($\bar{C}$) and extraterrestrial radiation ($\bar{H}_O$) can be estimated as:

$$\bar{H} = \bar{H}_O \left[a'' + b''(\bar{C})\right]$$

where

$\bar{C}$ = mean daily cloud cover for the given month

a'', b'' = empirical constants

Droz (1985) found, however, that the statistical accuracy was quite poor for predicting solar radiation with this equation. The sunshine method, thus, may be preferable to the cloud cover method if weather data information on sunshine hours exists for an area.

Rainfall Method. A third relationship which could be important in the tropics is the relationship between rainfall and solar radiation. A study used by Schaller and Larson (1983) estimated the relationship between average daily precipitation (rainfall) in inches and the clearness index (K_T). They found the relationship in or near tropical oceans to be:

$$K_T = \bar{H}/\bar{H}_o = c \exp(d\,'p)$$

where

$'p$ = average daily precipitation in inches
exp = exponential
c = .726, constant
d = .877, constant

As rainfall data are generally far more precise than visual estimations of cloud cover, this method is preferable to cloud data if good rainfall statistics exist and percent sunshine data are lacking. For instance, Droz (1985) found both sunshine and rainfall methods to be more statistically reliable than the cloud cover method which gave poor estimates in regression equations.

As noted earlier, estimating techniques may not necessarily yield better estimates of solar radiation than the simple "rules of thumb" presented earlier. However, these methods provide a way to easily check crude estimates to see if the numbers can be trusted at all.

Sources of Solar Data

A number of sources of solar energy information are available but the quality and therefore the utility for most is often too low to be more than marginally useful. The best data source usually is the local weather service; in some countries, these services have compiled extensive solar measurements from at least a few sites and may have even analyzed them for solar energy purposes. Agricultural experiment stations sometimes collect solar data for correlations of evaporation or plant growth measurements. Universities or their field stations may have instruments installed for research purposes. Other governments, including Australia, the United States, and New Zealand, collect and analyze meteorological data throughout the Pacific and may provide not only raw data but also specific analyses at minimal or no charge. Several atlases of global solar radiation exist but their information is too general and nonspecific to be useful for Pacific planning purposes.

An indirect source of solar data is often overlooked but, when available, is perhaps the most valuable of all. Present users of solar devices can provide valuable insight into both the actual availability of solar energy at specific sites and the problems associated with

Table 4.11. Monthly Average Daily Radiation for Yap

		Jan	Feb	Mar	Apr	May
Reflectance		.15	.15	.15	.15	.15
Clearness Index		.476	.553	.570	.519	.493
Tilt Angle						
0.0	I:	4.183	5.234	5.766	5.374	5.055
	SD:	0.435	0.374	0.362	0.397	0.419
5.0	I:	4.330	5.372	5.819	5.335	4.960
	SD:	0.448	0.382	0.365	0.395	0.413
10.0	I:	4.454	5.480	5.841	5.269	4.841
	SD:	0.459	0.389	0.368	0.393	0.406
15.0	I:	4.553	5.557	5.829	5.175	4.700
	SD:	0.469	0.395	0.369	0.390	0.398
20.0	I:	4.628	5.603	5.786	5.054	4.537
	SD:	0.478	0.400	0.370	0.386	0.390

Source: Schaller and Larson (1983).

Notes: Latitude = 9.8 degrees; units in kWh/m^2 · day; I = irradiance (kWh/day); SD = standard deviation.

particular solar units. In a location where a number of similar installations are to be made (for example, a standard type of remote telecommunication unit), a "demonstration" unit should be installed. The unit should be monitored to determine its performance. Based on that unit's performance, the location's solar availability can be determined and the required number of solar panels can be estimated. As additional units are installed and more data become available, the country can be categorized into regions defined by the determined area of solar panels needed to perform. For example, if a particular unit requires one photovoltaic panel to function properly in an excellent solar environment, then two may be required for a satisfactory region and three for a poor one. As more installations are made the regions become well defined, thereby improving the quality and economy of similar installations and defining the relative solar energy levels within the country for other types of solar units. The same process is adaptable to water heaters and other photovoltaic devices.

Another source that should be tapped for information is local resident observations. While such information about sunshine hours or cloudiness is much less definitive than instrument observations, it can provide basic information to help categorize a site. The surveyor

Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
.15	.15	.15	.15	.15	.15	.15	.15
.476	.357	.349	.408	.468	.468	.476	.468
4.813	3.662	3.620	4.163	4.498	4.178	4.065	4.551
0.435	0.603	0.614	0.523	0.444	0.444	0.435	0.457
4.699	3.599	3.588	4.172	4.579	4.309	4.223	4.582
0.427	0.594	0.610	0.525	0.451	0.455	0.449	0.459
4.564	3.521	3.539	4.161	4.636	4.417	4.358	4.590
0.418	0.583	0.604	0.526	0.457	0.466	0.462	0.461
4.408	3.428	3.474	4.129	4.669	4.502	4.470	4.575
0.409	0.572	0.598	0.526	0.462	0.475	0.473	0.461
4.234	3.321	3.394	4.076	4.677	4.563	4.558	4.536
0.398	0.560	0.590	0.525	0.467	0.484	0.483	0.461

must ask the right questions and avoid phrasing them in such a way as to make the local person answer in a specific manner. For example, it is valuable to ask a number of people within a region about the weather. Solar energy should not be mentioned. Instead, a third of the group is questioned about the number of days it rains, a third is questioned about the number of days it is cloudy, and the third group is questioned about the number of days of sunshine. By this method of cross-checking, a more realistic estimate of sunny days can be obtained than through a single line of questioning. It is important that the surveyor avoid leading those questioned to believe that any decision affecting them will result from the survey, since that inevitably skews the data. Instead, the survey should be specified simply as a data-gathering operation. It also helps if the survey includes irrelevant questions (such as the size of family, types of produce grown, etc.) to disguise which questions are important.

Empirical data on solar radiation in the tropics, and in particular in the Pacific islands, are limited to several studies using auxiliary data. In the Energy Mission Reports (1982), photovoltaic system economics were estimated for Fiji, Vanuatu, and the Cook Islands. The Hawaii Natural Energy Institute has collected data on daily solar radiation (insolation) studies in Micronesia and American Samoa. Schaller and Larson (1983) recently completed an in-depth analysis of the potential use of photovoltaics in the Republic of Palau, the Federated States of Micronesia, the Republic of the Marshall Islands, and the Territory of American Samoa. One program developed by the researchers estimates monthly average daily solar radiation for various islands in these countries. Table 4.11 presents daily radiation estimates for Yap based on this study.

Planning Based on Resource Availability

Priority areas for solar installations need to be identified for planning purposes. By plotting all data points (pyranometer sites, sunshine hour measuring sites, cloudiness percentage measuring sites, existing installations, and sites where surveys have been made) patterns will become visible, allowing the identification of areas having a good, satisfactory, or poor relative solar resource. Technical performance can be expected to be the best in the best resource areas. Economic performance includes other factors—the cost of alternatives and the value placed on energy are the primary ones—so the resource availability may not be the primary factor involved but is still an important part of the evaluation.

Solar usage falls into two fairly sharply defined categories. First is the large-scale unit for interisland telecommunications, irrigation pumping, or heating relatively large amounts of water for an industry or hotel. The second group will include a large number of small units for heating water or providing individual electrical power for homes.

In both cases, it can be expected that the better the solar availability, the better the unit will perform and therefore the better will be the economic benefit of the unit. Therefore, as solar energy becomes an increasing part of the total energy strategy of each country, it is reasonable to first develop those areas with high levels of solar energy and designate those with low levels as low-priority sites. Through such a strategy, the knowledge gained from a slower, prioritized implementation scheme can be used in future development plans.

HYDRO RESOURCE ASSESSMENT

Hydro power is a significant undeveloped resource on most mountainous islands of the Pacific. Since it is a site-specific technology, development costs of a hydro resource cannot be predicted in general, only on an individual location basis. Since the energy resource, flowing water, is variable, long time periods–typically five years or more–are needed to accurately evaluate a stream for its hydro resource. Because of the high costs of conducting a proper long-term stream survey, it is important to examine in detail only those streams with reasonable potential. The next section describes a general resource assessment using data usually readily available to make such first-cut analyses. To determine the total resource, detailed field studies are needed in addition to the general resource assessment.

Hydro Power Equations

The amount of power that can be generated by a hydro plant is a function of the available water flow in the stream or river and the head. The higher the head, the greater the power; likewise, the greater the stream flow, the greater the power. Thus a small 20-liter-per-second stream feeding a high 100-meter head hydro plant will generate about the same power as a large 200-liter-per-second stream flowing through a low 10-meter head plant. Because of seasonal variations, the water flow of a river or stream can vary significantly during a year, making it extremely important to get estimates of low and high flows. Three flow estimates–the monthly low, high, and average dependable flows–ideally should be known before power is calculated and a hydropower site is chosen. The energy analyst and hydro engineer use the estimates to calculate the range and duration of power outputs expected from a river or stream.

The energy analyst should be aware of several terms applicable to hydro calculations. **Flow or water discharge** is the volume of water flowing in a stream per unit of time, measured in cubic meters per second (m^3/sec), liters per second (l/sec) or cubic feet per second (ft^3/sec). **Head or hydraulic head** is the difference in height (elevation) between the water intake and the turbine inlet. A **weir** is, in general, a structure or a small dam that blocks a stream. In the case of resource assessment, it is a specially constructed small dam (called a **contracted weir** and sometimes called a **channel still**) with a calibrated opening to allow stream flow measurements. **Storage pond** refers to water accumulated in a natural or man-made pond intended to store water for future use. Its long-term use is to average the stream flow and make the effects of short-term changes in stream conditions less problematic.

Run of the river refers to a hydro system without a storage pond. This approach is used only when the total stream flow is significantly greater than the flow required by the turbine or when the turbine can be operated at varying outputs corresponding to water availability. **Runoff** is the water that stays on the surface of the ground after precipitation and runs directly into streams. **Groundwater** is water that has penetrated the ground and either remains there or flows through gravel, sand, or permeable rock underground. **Stream watershed** is the ground surface whose runoff flows into the stream, or all land bounding the stream that slopes toward the stream.

Flow duration curve is a plot of flow versus percent of time a specified flow can be expected to be exceeded, a basic display of stream characteristics. The graph has a vertical axis of flow and a horizontal axis of percentage. Because of the wide range of flows possible in a stream, the vertical (flow) axis is usually logarithmic. The maximum flow will be at the 0 percent point, the minimum flow will be at the 100 percent point, and the shape of the curve between the points indicates the stream variability.

An approximation of available power is given in the following equation:*

$$\underset{(\text{kW})}{\text{Power}} = (6.4) \times \underset{(\text{m}^3/\text{sec})}{\text{Flow}} \times \underset{(\text{meters})}{\text{Head}} \qquad (4.26)$$

$$\underset{(\text{HP})}{\text{Power}} = (1/8.8) \times \underset{(\text{ft}^3/\text{sec})}{\text{Flow}} \times \underset{(\text{ft})}{\text{Head}} \qquad (4.27)$$

Flow is determined by estimating first the area and second the average velocity (V_{avg}) of a stream. Two equations (4.28 and 4.29) needed for estimating flow are:

$$\text{Area} = \text{Width} \times \text{Depth} \qquad (4.28)$$

where

Area = area of stream (m^2 or ft^2)

Width = width of stream (m or ft)

Depth = average depth (m or ft)

$$V_{avg} = (0.9)\ (V_s) \qquad (4.29)$$

where

V_s = surface velocity of stream (m/sec or ft/sec)

V_{avg} = average velocity of stream (m/sec or ft/sec)

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* See Merrill and Gage (1978) for another equation using British units.

Thus flow is calculated as follows:

$$\begin{array}{llll} \text{Flow} & = V_{\text{avg}} & \times & \text{Area} \\ (\text{m}^3/\text{sec}) & (\text{m/sec}) & & (\text{m}) \\ (\text{ft}^3/\text{sec}) & (\text{ft/sec}) & & (\text{ft}) \end{array} \tag{4.30}$$

Several methods can be used to measure the flow and head of a stream or river. These methods differ according to the river or stream size and the measurement equipment available to the energy analyst. For small- to medium-sized streams where micro- or mini-hydro units may be installed, three methods used to measure water flow are the float, the volume, and the weir methods. The float and volume methods are mostly used in small streams, whereas the weir method can also be used in medium streams. Each technique is described in detail in the later section on field studies. Measuring the head is discussed in the section on study priorities.

Identifying Potential Sites: Mapping the Resource

Before going to the field, "desk" studies can be made to readily identify the best hydro sites for field studies. However, in micro-hydro construction, the site is the main consideration. The majority of the cost in a micro-hydro installation is the civil works necessary to capture and direct the stream to the turbine and the transmission/distribution system needed to transfer the power to the user. Even with detailed stream flow data and high-quality contour maps, the cost of a micro-hydro installation cannot be accurately estimated without a detailed site visit. A desk survey can best determine the streams with potential too small or distance too great from power users to be practical.

The basic requirement for general resource assessment is a high-quality contour map (sometimes called a terrain map), preferably with contours separated by no more than 30 meters (or 100 feet if not a metric scale map). Military maps (obtained from the Australian, British, and U.S. governments) often have better terrain definition than comparable civilian maps but may require considerable correction for habitation changes since they often date from World War II. Using the contour map, the analyst should take the following steps:

1. Check the presence of all villages and potential power users on the maps and estimate their minimum power requirements. Since many maps of the Pacific are more than a decade old, some villages may not appear on the maps and other villages on the maps may have disappeared from existence. Census, electrical district,

education, and health personnel usually can assist in locating villages and providing current population information. This step locates the possible electricity users and allows forecasting of the required amounts.

2. Draw in the existing electrical grid with the line voltages marked or color coded. This locates the areas already electrified and possible connect points for hydro sets to add their power to the existing grid.
3. Add to the map all rain gauge locations and label with annual average rainfall measured at each site.
4. Include on the map the average flow of any streams that have been measured. Such hydrographic information may have been compiled by the public works department or the agency that is in charge of the public water supply. Also, universities, agricultural departments, existing hydro power stations, and aid agencies are likely sources of hydrological information.
5. Locate waterfalls on the map and include information concerning stream flow and height of fall.
6. Locate any flood control, water supply, or irrigation dams on the map and outline the resulting reservoir if not already shown.

At this point in resource map development, the analyst can eliminate impractical areas from further consideration. Impractical hydro areas include

- Flat areas without dams, since low-head hydro systems cost more than medium- and high-head systems because of dam requirements (unless a multipurpose dam is practical and capital costs can be spread over several functions such as water supply or irrigation);
- Streams with watersheds in low rainfall areas, unless high heads are present; and
- Areas too far from the grid or load centers to be financially practical. Economic distance depends on the cost of alternative means of power generation, the size of the power requirements, the cost of building transmission lines, and the cost of developing the hydro site itself. A rough rule of thumb for hydro plants under 100-kilowatt capacity is if a load center requires Y kilowatts capacity, a hydro plant located farther than 100 times Y meters away should be very carefully evaluated in terms of financial costs. Thus if a village requires a 10-kilowatt capacity then the hydro plant probably should not be more than 100 times 10 meters (1000 m or 1 km) away.

Once the impractical areas for hydro use as a power source are eliminated or relegated for later study, the remaining streams should be evaluated through setting study priorities and making field surveys as described in the following sections. For each stream and its tributaries in those areas selected for further study, the analyst will draw in the boundaries of the stream's watershed. This is done by connecting all ridge points on the contours. When correctly drawn, the watershed area sketched on the map will only have downward slopes toward the enclosed stream, will fully enclose the stream except where bounded by a lake or an ocean, and will not overlap another stream's watershed area. The watershed boundary line will always cross contours at right angles, and the contour curves always enclose higher areas and point toward lower ones. The watershed that contributes to stream flow at any point can be found by drawing lines from the stream point perpendicular to the contours until the outer boundary of the watershed is reached. The watershed area uphill from the selected stream point will be the watershed that contributes flow to that point.

Setting Detailed Study Priorities

The high-priority sites for detailed examination will be those that are close enough to main electricity load centers to allow power transmission at reasonable cost and have sufficient power availability to make development worthwhile. Many possible sites may exist along the stream. The quality of a site is a function of (1) the stream flow present (determined by the size of the watershed upstream from the site and the rainfall on that watershed minus that water used for other purposes and not returned to the stream); (2) the stream slope at the site (the head divided by the distance between intake and turbine); and (3) the distance to the load center. In selecting a tentative site on a stream, all these factors must be considered, but the most important for small units are often the available head and distance from the local load center. For this first-cut selection it is probably best to choose tentative sites that have the steepest slopes close to the load, but the analyst must examine all the streams within the load access area, not just the first promising stream.

To determine which areas have the best load characteristics, draw lines around small load centers (those requiring 100-kW capacity or less) which are at a distance (in meters) of 100 times the load requirements in kilowatts. For villages, the result will be a circle around the village. For areas where grid connections are possible, assume a band 20 kilometers on either side of the existing power lines, unless it is known that the lines can accept less than 200 kilowatts; in that case, assume a band the distance the lines can accept (in kilowatts) divided by 10. For this first examination, only hydro sites within the boundaries circling load centers or banding existing power lines are considered. The area inside the boundaries is called the **load access area.**

After mapping land characteristics, rough power estimates can be mapped by using proxies. Power availability increases according to the product of stream flow times the head. As stream flow increases with increased watershed area and average watershed rainfall, stream flow is proportional to watershed area times average rainfall over the watershed area. For example, a site whose stream has a watershed of 10 km^2 and an annual rainfall of 3000 mm can be expected to have water flows similar to a different site with a watershed of 15 km^2 and rainfall of 2000 mm. By mapping rainfall and watershed size data, we get an idea of the stream flow prior to actual measurement.

Head is the difference in height (ft or m) between the water intake for the turbine and the turbine itself. To categorize sites by head, divide the height of head by the horizontal distance between the proposed system's intake point and the hydro system's turbine site. The larger this number, the steeper the drop to the turbine and usually the lower the equipment cost to transport the water between intake and turbine. The turbine will be located some distance downstream from the intake. To get to the turbine, the water must be taken from the stream and transported (usually by a pipeline called a **penstock**) to the turbine. A waterfall site will have a high priority while a cascading stream site will have a lower priority.

With the above information, a reasonable priority for taking the next step of making detailed field studies can be made. If reliable rainfall data are available, a **priority factor** may be obtained by multiplying rainfall times watershed area, then multiplying that figure by the head divided by the distance between intake and turbine.

Using an equation, this priority number is equal to:

$$\text{Rainfall} \times \begin{array}{c}\text{Watershed}\\\text{Area}\end{array} \times \begin{array}{c}\text{Head/Intake to}\\\text{Turbine Distance}\end{array} = \text{Priority Index} \qquad (4.31)$$

Note that the priority number is proportional to the power available at the site assuming that all our assumptions about rainfall, watershed, penstock cost, and transmission lines costs are correct. Unfortunately these assumptions are likely to be in considerable error so it is recommended that the list of sites be divided into three groups: the top one-third high priority, the middle one-third medium priority, and the bottom one-third low priority. Then analysts can examine the high-priority list and choose sites for immediate study on the basis of other factors such as ease of access (important for building dams, penstocks and powerhouses), the power needs in the area, or political requirements.

In summary, sites that have obvious promise will be ones: (1) that are close enough to load centers or a usable grid connection point to have cost-effective transmission of power; (2) that have watersheds of a sufficient size and in an area of sufficient rainfall to generate adequate year-round flows; and (3) where the stream falls fast enough to allow sufficient head to be obtained at a reasonable civil works cost. If, as is likely for larger islands, rainfall data are too inadequate to be useful for many sites, priorities for further study cannot be determined from data but rather have to be estimated considering all natural, economic, and political factors. Even without sufficient rainfall data, areas of high, low, and intermediate rainfall are usually known from resident observations.

Someone with field hydro surveying experience will be of great value at this stage. It is best, however, not to employ outside experts until all the maps have been prepared with all available data; otherwise, much of the specialist's time will be spent gathering data instead of analyzing the data and judging site suitability.

Field Studies: Making Stream Flow Estimates

"Desk" exercises can assist in assigning field study priorities for possible sites, but hydro development is so site-specific that no development should ever take place without field study. The scale of field study may be small for a development that will use only a small percentage of a stream's flow or may be large if maximum stream utilization is desired. All field studies require specialists to examine several categories.

HYDROLOGY

Hydrology involves determining the stream flow characteristics. Characteristics to be determined are maximum and minimum stream flows, the height of water in flood, the average flow, the flow duration curve, and seasonal stream flow variations. Minimum flow is probably the most important value since that characteristic determines the minimum continuous power available at the site. If the minimum flow is adequate to provide the power needed at the load, then a lower-cost run-of-the-river installation may be used. If the minimum flow is not enough but the average flow is adequate to generate the needed power, a storage pond will be necessary. If the average flow is not enough, then other streams may need to be diverted into the flow to raise the level to the load requirement. Maximum stream flow and flood height data are necessary for intake structure design and to ensure that the power house is located above flood levels.

Since hydrological data are the basis for estimating hydro capability, data gathering should last several years and begin as soon as a site is seriously considered. The installation of stream measuring stations, either with automatic instruments or with weirs checked daily, should have priority. Five years' worth of data is the minimum for proper analysis, but decades of data are preferred when large systems are to be built.

Sites where variable power availability is not a problem have fewer technical requirements for detailed hydrological study, but the site's economics change considerably with changing stream flows so hydrological study remains important.

Small streams with proposed hydro units below 10 kW in size, particularly those sited on streams that clearly have more flow than is needed, require much less study. Besides actual measurements, residents should be surveyed for estimates of minimum stream conditions, both in quantity and seasonal patterns, and maximum flood conditions. These can usually be determined with fair accuracy through resident interviews and examination of streambanks for flood evidence.

Field estimates of small stream flow are not difficult. The three alternative methods are listed in order of increasing accuracy and difficulty (Merrill and Gage 1978):

Float Method. Find a section of the stream that has a fairly smooth bottom and changes minimally over a length of 5 m (Figure 4.2). Measure the width and depth of the stream in meters. Calculate an approximate cross-section area by multiplying the width times the average depth. Average depth is the sum of individual depth measurements divided by the number of measurements. For example, if a stream's depth is measured at six places, the sum of these depths is divided by six (Figure 4.2). Place a floating object in the center of the stream and determine the amount of time it takes the float to move downstream a measured distance (1 m for slow streams; as much as 10 m for fast ones). Convert that time to speed in meters per second by dividing the meters traveled by the measured time. The approximate stream flow, in cubic meters per second, will be the cross-section area of the stream times the stream speed. The formula is:

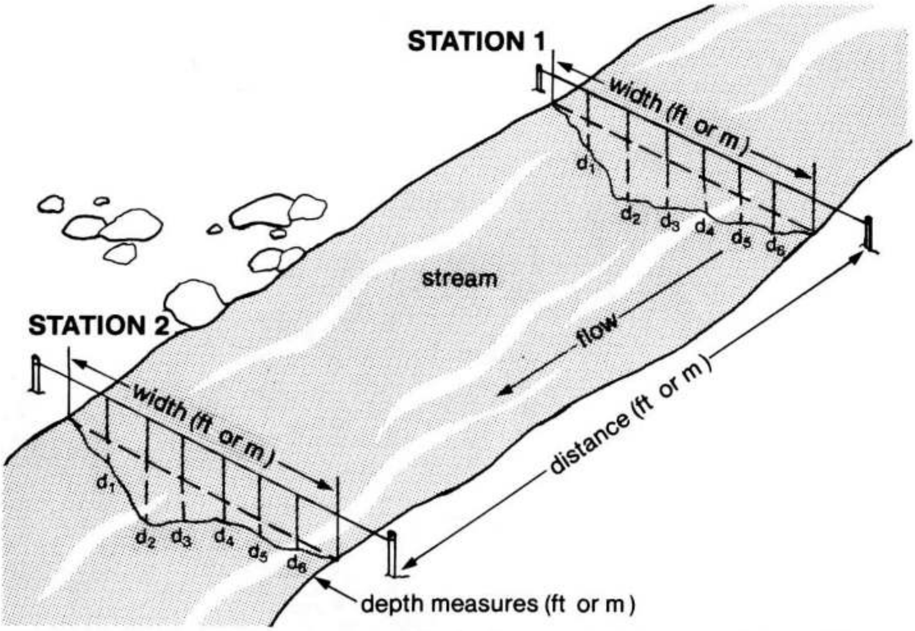

Figure 4.2. Estimating stream flow with the float method (Source: Adapted from Merrill and Gage 1978).

Flow = Width × Average Depth × Stream Velocity

Volume Method. For very small streams, divert the stream into a container of known volume and measure the time it takes to fill. A 200-liter drum, for example, filled in 10 seconds indicates a stream flow of 200/10 or 20 liters per second. Since there are 1000 liters in a cubic meter, that is 20/1000 or 0.02 m^3 per second. The volume method is useful mainly for a small cascading stream where a container can be placed under a waterfall or the total stream's flow can be easily diverted into the container. The accuracy of this method is dependent on whether all the stream can be diverted into the container; if so, the measurement is accurate.

Weir Method. It measures the height of the water flowing through a weir, which may be a permanent installation intended for a long series of measurements or a temporary wooden structure. Figure 4.3 shows the important parts of the weir and Table 4.12 allows the measurement to be converted into stream flow. Where a permanent weir is not practical, a temporary wooden weir installed during the season of minimum flow can provide weeks or months of low-flow data and help establish the site's minimum power availability.

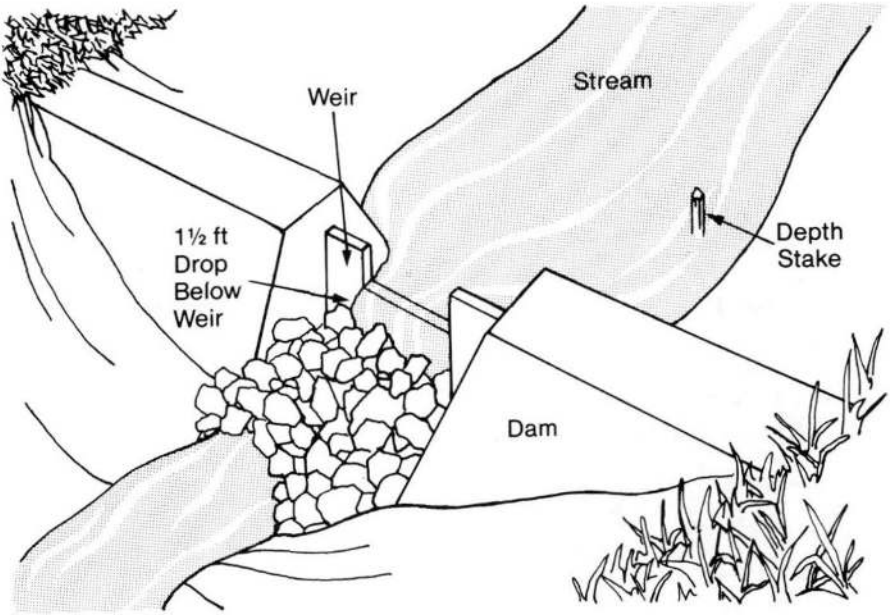

Figure 4.3. Estimating stream flow with the weir method (Source: Adapted from Merrill and Gage 1978).

PHYSICAL SURVEY

Land surveyors should make a detailed **physical survey** of the area on either side of the stream to at least 10 m above the level of the proposed intake structure to the level of the tailrace (the water outlet from the turbine). The survey should include the upstream area that would be included in a storage pond. If the actual location of the intake structure is not fixed by stream characteristics or other factors, the survey should be made over a larger portion of the stream to assist in locating the best placement for the intake structure. A **level line** from the intake site should be staked on the ground on both sides of the stream. The level line is the upper limit for the diversion channel path since it cannot be higher than the intake structure. This line will be used to plan the path of the water transport system, be it an open channel or a closed pipe. The contour distance is dependent on the size of the installation. Small (20 kW and less) sites should have no greater than 1-meter contours in the storage pond area and no more than 2-meter intervals for the rest of the survey. Larger sites may have greater contour intervals overall but closer intervals along water transport routes, at dam sites, and at the power house.

Table 4.12. Flow Conversion Table for Weir Method

Head (feet)	Q (cfs)	Head (feet)	Q (cfs)	Head (feet)	Q (cfs)	Head (feet)	Q (cfs)
.05	.037	1.05	3.51	2.05	9.37	3.05	16.66
.10	.105	1.10	3.76	2.10	9.71	3.10	17.05
.15	.193	1.15	4.01	2.15	10.05	3.15	17.45
.20	.297	1.20	4.27	2.20	10.39	3.20	17.84
.25	.414	1.25	4.54	2.25	10.73	3.25	18.24
.30	.544	1.30	4.81	2.30	11.08	3.30	18.65
.35	.685	1.35	5.08	2.35	11.43	3.35	19.05
.40	.836	1.40	5.36	2.40	11.79	3.40	19.46
.45	.996	1.45	5.65	2.45	12.14	3.45	19.87
.50	1.17	1.50	5.93	2.50	12.51	3.50	20.28
.55	1.34	1.55	6.23	2.55	12.87	3.55	20.69
.60	1.53	1.60	6.52	2.60	13.23	3.60	21.10
.65	1.72	1.65	6.83	2.65	13.60	3.65	21.53
.70	1.92	1.70	7.13	2.70	13.97	3.70	21.95
.75	2.13	1.75	7.44	2.75	14.35	3.75	22.37
.80	2.34	1.80	7.75	2.80	14.73	3.80	22.79
.85	2.57	1.85	8.07	2.85	15.11	3.85	23.22
.90	2.79	1.90	8.39	2.90	15.49	3.90	23.65
.95	3.02	1.95	8.71	2.95	15.88	3.95	24.08
1.00	3.26	2.00	9.04	3.00	16.26	4.00	24.52

Source: Merrill and Gage (1978).

Note: This table applies to rating the flow (Q) in cubic meters over a rectangular weir. To derive the actual flow rate of a stream, multiply the given flow value (cubic feet per second per foot of width of the weir) times the width of the weir (feet).

The transmission line route can be determined from a rough survey of the area between the power house site and the load center. Then a detailed survey should be produced for that route and for any distribution paths needed in the load center itself. If access roads are required, routes can be determined from a rough survey, but a detailed survey is required when the actual route is to be built.

GEOLOGICAL SURVEY

A **geological survey** should examine the intake site and dam site (if any) for the capability of the ground to carry the weight of the intake structure, dam, and storage pond. The presence of porous rock, gravel, or other possible sources of storage pond leaks needs to be established.

The survey also must determine the quality of foundation rock for the dam, the presence of rock that will have to be removed for penstock runs, the quality of rock for attaching steep runs of penstock, the quality of foundation material for the power house, and the amount and type of solids transport to be expected in the stream from the watershed.

The geologist should also examine the earth stability at the site to determine the possibility of land slippage, which might damage components of the installation. Access routes to the site should be determined with the assistance of a geologist or soils engineer to prevent soil destabilization on slopes and land slips from the construction activity.

ELECTRICAL USE SURVEY

In a **detailed electrical use survey**, the load center should be examined for electrical use patterns including peak use, average use, and minimum use. In particular, if any seasonal use is likely (as with an agricultural processing plant), that use must be matched with water flow patterns to determine the stream's capability of meeting maximum loads.

In conclusion, the detail of the surveys and the time spent gathering field data should be in proportion to the size of the site. If a number of small sites are to be examined, one of the most cost-effective methods is to create a team including three physical surveyors, a geologist, two electrical surveyors, and a hydrologist. A small site typically takes four days to conduct a minimal survey that can provide data adequate for rough power availability and limited financial calculations. For larger sites, teams are often created solely for site examination and may stay on location weeks, months, or even years at a time.

WIND RESOURCE ASSESSMENT

Although almost all meteorological reporting stations provide wind observations, determining wind energy resources from the data is surprisingly difficult. First, wind instruments at meteorological stations are positioned at heights where there may be interference from surrounding trees, buildings, and terrain. Second, sites are often at airports, which are selected specifically for their low winds. Also, in developing countries the need for wind energy tends to be in areas far from centers of population, while meteorological observations tend to be near population centers.

To adequately determine a national wind resource all possible wind data sources should be included in the assessment. By combining many different data sources, maps of **relative wind resource** may be drawn. Detailed measurements to provide accurate, detailed wind energy estimates can then begin in the areas that show the most promise. The energy specialist should be familiar with several terms related to wind resources. **Prevailing wind** is the most common wind direction during a specified period of time. Some locations have prevailing winds that almost never vary. Prevailing winds at other sites may vary seasonally, daily, or even hourly. It is not unusual for island winds to be prevailing from the sea during the day and to the sea at night. **Energy wind** is a wind blowing hard enough to produce useful power from a wind machine. Although each type of wind machine begins to produce power at a different wind speed, 4 meters per second (about 9 miles per hour) is a reasonable speed to use for preliminary analysis. By that definition, any wind greater than 4 m/sec is an energy wind. A **gust** is an abrupt change in wind speed. The change lasts only a few seconds.

Run of the wind is a measurement indicating the total air movement past the measuring site during the measurement time period. For example, a 7-m/sec wind blowing for 3 seconds results in a 21 meter run of the wind. Since there are 3600 seconds in one hour, a 3-m/sec wind blowing for one hour results in a 10,800 meter (3 X 3600) run of the wind; since there are 1,000 meters in a kilometer, that is a 10.8 km run of the wind.

For a more complex example, assume a 10-m/sec wind blows for two hours, a 20-m/sec wind for four hours, a 15-m/sec wind for nine hours, and a 5-m/sec wind for nine hours, then the kilometers of wind for that 24-hour period are:

$$\begin{aligned} &(10)(2)(3600) + (20)(4)(3600) + (15)(9)(3600) \\ &+ (5)(9)(3600) = 1{,}008{,}000 \text{ meters run of the wind} \\ &1{,}008{,}000/1{,}000 = 1{,}008 \text{ kilometers run of the wind} \end{aligned}$$

Run of the wind divided by the number of hours used to produce that run gives average wind speed for that period of time. For the above example, 1008/24 = 42 kilometers per hour average wind speed. Meteorological wind measuring devices (anemometers) often provide output in run of the wind and instantaneous velocity. Older measurements may list units in "miles of wind," since miles per hour rather than meters per second used to be the standard. **Free air velocity** is the speed of the wind that is clear of the ground and obstructions—i.e., the "natural" wind speed. Variations from the free air velocity are due to the presence of trees, hills, buildings, and other objects that are in the wind's path. Sometimes it is called "gradient wind."

The **velocity gradient** reflects the fact that the wind moves much more slowly near the ground than at increasing heights above the ground. The increasing velocity with increasing height is called the wind velocity gradient and is determined by the speed of the wind, the character of the ground surface, and the presence of obstructions. Over a large flat surface, such as a desert, free air velocity will be reached at a lower height than over a grove of 100-foot coconut trees.

A **wind rose** is a graph of wind data for a given time period. The graph is made by plotting wind data on a compass "rose." The direction of the wind is represented by the direction on the compass diagram and the speed by distance from the center of the diagram. This provides a valuable visual display of the prevailing winds.

Wind Power Assessment Equations

Before describing potential data sources, background equations are needed to measure wind energy from energy data. Wind power is basically the rate of change of kinetic energy in air. The kinetic energy in a quantity of air mass (m) that moves at a given wind speed (velocity) is simply:

$$\text{Kinetic Energy } (E_K) = \tfrac{1}{2}\,(\text{Air Mass})\,(\text{Velocity})^2 = \tfrac{1}{2}\,mV^2 \qquad (4.32)$$

Since power is the rate of change of kinetic energy over time:

$$\text{Power} = \frac{dE_K}{dt} = \tfrac{1}{2}\,\dot{m}\,(\text{Velocity})^2 \qquad (4.33)$$

where d = instantaneous change

$\dot{m}$ = the mass of wind flowing through cross-sectional area (A) of wind machine blades per second; $\dot{m}$ = (Air Density) (Area of Blades) (Velocity)

Using the above equation for wind power and substituting for $\dot{m}$, power can be expressed as:

$$\underset{(\text{kW})}{\text{Power}} = \tfrac{1}{2}\,(\text{Air Density})\,\underset{\substack{(m^2)\\(ft^2)}}{(\text{Area of Blades})}\,\underset{\substack{(m/sec)\\(mph)}}{(\text{Velocity}^3)} \qquad (4.34)$$

Looking at Equation 4.34 for wind power, obviously wind speed (velocity) is the critical variable in the equation, since power is directly proportional to the **cube** of the wind speed, e.g., a doubling of wind speed gives an eightfold power increase ($8 = 2^3$). Thus, accurate wind speed measurements collected over time are important for assessing a potential wind conversion site. However, estimating ultimate wind energy at a site is technology specific in that each wind machine has different blade areas. These equations will be discussed in Chapter 5 in the wind technology section.

Because of the importance of wind speed to power output, wind's erratic nature creates end-use problems for power generation. Wind conversion systems have a limited range of wind speeds at which they can usefully and safely operate. Too low of a wind speed means little power output, while too high of a wind speed is dangerous and systems are designed to automatically shut down. Thus, sites which have the best potential for wind power are areas with steady, strong winds with minimal wind changes.

In practical terms, the lowest wind speed for which wind pumping systems are useful tends to be 9 miles per hour (4 meters per second). Areas with winds between 12 and 25 mph (7 and 16 m/sec) are considered good candidates for electricity generation.

Sources of Wind Resource Information

Most sources of wind information do not provide sufficient detail to be more than marginally useful. The best source usually is the local weather service, which in most countries collects extensive wind data from at least a few sites and may even have analyzed it for wind energy purposes. Agricultural experiment stations often collect wind data, as do universities or their field stations. Some governments—notably Australia, the United States and New Zealand—collect and analyze meteorological data throughout the Pacific and may be able not only to provide raw data but also to conduct specific analyses at minimal or no charge. Several atlases of global wind patterns exist; this information is valuable in detecting major wind patterns such as the presence of monsoons, trade winds, or seasonal direction changes.

Marine departments, fishermen, and yachtsmen are also good sources of general information about large-scale wind patterns over the ocean. Be aware, however, that winds at sea are often radically different than winds over a mountainous island, though less so for an atoll. In particular, seasonal wind patterns of direction and strength can be learned from sailors.

One information source, often overlooked but perhaps the most valuable of all if available, is the present users of wind devices. Though currently small in number, users can provide valuable insight into the actual availability of wind energy at their site as well as any problems associated with a particular wind machine. In a project where a number of similar installations are to be made (for example, wind-powered water pumping units), performance of existing units should be monitored. As more units are installed, more data become available so that forecasting the performance of future installations is easier.

Energy analysts should tap local residents for their observations about wind patterns. While such information is less accurate than instrument observations, it can provide basic information. Perhaps the most important result of questioning local people about wind is in pinpointing the specific place in the area that has the most wind. Local people will likely know of hilltops and clear areas where wind blows the hardest. The surveyor must be careful to ask the right questions and avoid phrasing questions in such a way as to make people answer in a specific manner. For example, half of the group may be asked about the frequency of windy periods and half about the frequency of calm periods. Then the data may be cross-checked. Wind energy should not be mentioned during the survey. Instead the survey should appear to be simply a data-gathering operation with the results to be archived.

Remember that a site's suitability for a wind machine is often dependent upon the wind patterns, not just wind quantity, during a 24-hour period, so the survey should include questions about daily wind patterns and how often calm spells of more than a few days occur. Seasonal changes in wind patterns should also be questioned. An important part of the design of the local resident survey is to create wind speed definitions that are as objective as possible. It is less useful to ask, "How often does the wind blow hard?" than it is to ask "About how many months does it blow hard enough to make the coconut trees bend?" If the site is near the sea, the analyst should use Beaufort-scale indicators (Table 4.13) and specifically talk to people who regularly fish or at least spend many hours near the ocean.

In temperate zones, considerable work has been done using natural indicators. Natural indicators include trees misshapen from continuing high winds and certain patterns of vegetation growth. Unfortunately, little study of such indicators has been done in the Pacific islands, and whether the work that has been done is directly applicable in the islands is not known. Certainly, such indicators exist, as evidenced by

Table 4.13. The Beaufort Wind Scale and Approximate Wind Speeds

Beaufort Number	Sea Description	Land Description	Speed (m/sec)
0	Sea is like a mirror.	Smoke rises vertically.	0.–0.2
1	Ripples with the appearance of scales are formed but no crests.	Smoke rises at a small incline.	0.3–1.5
2	Small wavelets, still short but more pronounced. Crests have a glassy appearance but do not break.	Tree leaves quiver. A light wind can be felt on the face.	1.6–3.3
3	Large wavelets. Crests begin to break. Foam looks glassy and some scattered white horses.	Leaves and small branches move.	3.4–5.4
4	Small waves, becoming longer. Fairly frequent white horses.	Wind-blown dust and leaves on roads.	5.5–7.9
5	Moderate waves with a more pronounced form; many white horses. Some spray possible.	Small trees begin to sway.	8.0–10.7
6	Large waves begin to form; the white foam crests are more extensive everywhere. Some spray likely.	Large branches move. It is difficult to use an umbrella.	10.8–13.8
7	Sea heaps up and white foam from breaking waves begins to be blown in streaks along the direction of the wind.	Trees sway. Walking against the wind is unpleasant.	13.9–17.1
8	Moderately high waves of greater length. Edges of crests begin to break into spindrift. The foam is blown in well-marked streaks along the direction of wind.	Small branches break. It is difficult to walk outside.	17.2–20.7
9	High waves. Dense streaks of foam along the direction of the wind. Crests of waves begin to topple, tumble and roll over. Spray may affect visibility.	Branches of trees break.	20.8–24.4
10	Very high waves with long overhanging crests. Foam in great patches is blown in dense white streaks along the direction of the wind. Visibility affected.	Trees are uprooted. Structural damage.	24.5–28.4

Source: Adapted from Gentilli (1966).

wind-induced tree growth patterns at good wind sites in Hawaii. The difficulty in using the indicators is measuring wind speed and consistency. Studies have shown that natural indicators can be used as a measure of wind speeds but exactly which indicators show which speeds has yet to be shown for the tropics. Certainly, a group of trees with branches all growing in one direction is a good sign of high energy winds, and such a site should be high on the list for detailed evaluation.

Evaluation of the Wind Resource

Evaluating the wind resource is a matter of experience and judgment, unless equipment and methods designed to determine wind energy availability are used for measurements. It is recommended that someone experienced in wind energy resource assessment–not meteorologists unless specifically trained in wind energy analysis–be retained to perform an evaluation. If that is not possible, arranging the data in an organized fashion at least can help to determine the areas of the country where wind machines have the best chance of performing.

The first step in organizing wind data should be evaluating their quality. Each wind measuring station should be visited and assigned a wind energy data quality rating of good, average or poor. Note, please, that this rating is for wind *energy* data; a station may be perfectly adequate for meteorological data purposes and poor for wind energy data. The placement of the anemometer (wind speed measuring device) determines the quality of the station more than anything else. A *good* station is one with the measuring instruments at least 15 meters above all trees, terrain, and buildings within a 200-meter radius. An *average* station is one which has the measuring instruments at least 10 meters above all trees, terrain, and buildings within a 100-meter radius, and a *poor* station has the anemometer mounted less than 10 meters above all trees, terrain, and buildings within a 100-meter radius. While these classifications are arbitrary, they do assist in establishing the confidence level that should be assigned to data from a specific station. A history of the station, in particular the calibration and maintenance history of the wind instruments, is also useful in determining the probable quality of the data.

Separating the meteorological data, resident survey data, and any other types of data, the analyst should arrange the data sets from best to worst wind sites. Still further, break each data set into three categories: A (good wind sites), B (fair wind sites), and C (poor wind sites). Wind speeds at good sites are at or above 5 m/sec (11 mph), fair sites from 3–5 m/sec, and poor sites less than 3 m/sec.

Next, plot the data on a map. At each data site, write in the data category (A, B or C), using a different color for each set of data (meteorological, resident survey, wind machine owner, and such). For the meteorological data map, include the quality category of the station (good, average, or poor).

If wind speed patterns are to be determined using isolated data points, the assumption must be made that winds near the data sites are the same as those at the data sites. The likelihood of that being true is largely dependent on the terrain around the site and the quality of the instrument installation. In a mountainous site with a poor-quality installation, no assumptions should be made concerning sites separated by even a few hundred meters. For a good installation on an atoll, the data may be valid for tens of kilometers around the station. In determining patterns from the mapped data, it may be useful to draw a "radius of confidence" around the station with small (1 km or less) circles around mountain stations and large (10 km or more) circles around stations in flat terrain. The circles should be adjusted for the quality of the measurement system installed in the site.

When complete, patterns may be apparent, indicating the areas that fall under categories A, B, and C. If such patterns become clear, then contour-type maps can be prepared showing regions of relative wind. If patterns do not appear, it is probably because there are too few data sites. In that case, the data from the isolated sites cannot reasonably be inferred to be correct for the large area surrounding the sites, and evaluation cannot be carried further without data collection from more locations.

Always remember, however, that the actual wind energy available is almost certainly more variable than that indicated by average wind speed measurements and that it is very unlikely that the sites where data have been collected will include the best wind areas. For those reasons it is likely that a good wind site is near a station that records 5 m/sec or greater annual wind speed averages. But it is unwise to decide against installing wind machines or to avoid further study just on the basis of meteorological or resident survey data. The collected information should show those areas of the country where more elaborate, energy-oriented data collection efforts should be concentrated.

An important part of a wind evaluation is also an estimation of the maximum probable wind. Those countries in the hurricane belt may expect a site to be subject to 200-kph winds on a regular basis. Machines installed in those areas must be capable of either withstanding hurricane forces (unlikely for small machines) or being dismantled on a day's notice. Several tower designs allow the entire tower to fold over and the wind machine to be secured horizontally on the ground for the duration of a hurricane. This feature is critical for wind machines in Pacific island countries.

FIELD SURVEYS

Once general wind patterns have been established, those areas with the highest probability of having wind sites should be examined in the field. Finding good wind sites is less of a science and more of an art. The process has been compared to prospecting for gold, and many experts call field surveys "wind prospecting."

The survey team should be small (two or three persons) and be prepared to travel on foot through the area being surveyed. In general, if a site is a good one, the wind will make it a poor place to live and few trails or habitations will exist in the area. The crew should survey the area's residents, watch for wind-modified vegetation, and take short-term (a week, typically) wind measurements with a run of the wind anemometer mounted on a 5- to 10-meter temporary mast.

The anemometer data are then compared with the data for the same period taken at the closest long-term wind measuring station. Divide the average speed found at the prospecting site by the same period's average speed from the fixed station to get a multiplier. This multiplier times the data from the fixed station will provide an indication of the speed at the prospecting site.

Wind direction measurements usually are not important unless wind channeling or shading is a factor. In that case, it may be worthwhile to gather direction data as well as average wind speed data for correlation with the fixed instrument data. The correlations are so rough, however, that the value is of limited use and suggestive at best.

This short-term data-gathering operation should help locate the highest quality sites within the A or *good* general region on the map. The values of wind speed are still not accurate enough to make estimates of the power generation capability of a wind machine, which requires a more intensive data-gathering series.

SITE VERIFICATION

Once an apparently good site is located, more prospecting in the immediate area of that site is useful to find the best site in the area. Referring back to Equation 4.34 on power from wind, the difference of one-half meter per second in average wind speed is a significant increase in available power because power increases with the cube of speed. The highest speed of wind may not be at the top of a hill but may be down the slope in the direction of the wind. Be wary of sites that show signs of turbulence as evidenced by gusts not found in other nearby locations. Turbulent winds are not only an inefficient source of wind power, they are hard on wind machines and may cause early mechanical failure.

Two methods are used for site verification: (1) months or years of data from recording anemometers or (2) installing the wind generator and measuring its output. Rarely is it recommended that a wind generator be installed without extensive prior measurements at the site, but it must be remembered that the cost of setting up and operating the wind measurement facility may be more than the cost of installing a small wind machine–particularly one obtained through aid or from a manufacturer eager to have the machine tested in tropical field conditions. By using an experimental wind machine to evaluate the site for later machines, high-quality data are received and the machine is simultaneously tested. Later on, larger or higher quality machines can replace these earlier experimental designs. Ideally, a number of sites should be certified simultaneously. The simultaneous data received will aid in preparing correlations between sites, allowing more accurate estimates of the wind resource at each site.

5

ENERGY TECHNOLOGY ASSESSMENTS

Energy assessment requires an examination of both technologies and fuels. Choosing the right technology is important for matching end-use needs with resource supplies. Wise technology choices give flexibility for future growth or change.

The purpose of this chapter is not to compare various energy conversion technologies, since comparison is generally left to a country's energy analysts. Rather, the goal here is to discuss different conversion technologies and the fuels presented in Chapter 4 in regard to their conversion efficiencies, usable energy delivered to users, and input fuel demand. The format of this chapter resembles Chapter 4 and includes a brief discussion of the advantages and disadvantages of each technology, equations for making energy measurements, and applicable data for the systems.

Some precautions are helpful. Much of the data for the different technologies represent averages for well-run and well-maintained systems. Because of differences in technology design, current production capacity (utilization rate), fuel loading methods, fuel type, operator skills, and maintenance, such average values may not be accurate for conversion systems in urban or rural areas. However, average data are still useful to energy planners to understand general patterns and differences among technologies.

STOVES

The primary use of energy in rural areas is for domestic cooking. Since fuel collection, food preparation, and cooking consume considerable labor and material resources in villages, improving stove types and thus improving fuel efficiency has been the goal of many international and domestic stove programs. Most Pacific stove programs have concentrated on developing more efficient stoves with less smoke output. An important requirement of any "improved" stove is that it must actually use less fuel or reduce smoke for cooks.

Stove Efficiency Measurement Problems

The major problem with estimating stove efficiency is deciding what use—boiling, cooking, or simmering—to measure. In measuring stove efficiencies, stove use differences are extremely important to the efficiency measurement. Because of these problems, three standardized stove efficiency test procedures have been developed by VITA (1983): the **water boiling test** (WBT), **controlled cooking test** (CCT), and the **kitchen performance test** (KPT).

WATER BOILING TEST

The WBT measures stove efficiency when water is boiling in a pot. The tests are made under controlled laboratory conditions. Most researchers recognize the inherent problems and limitations of this test procedure. The vessels used for boiling water influence the results (e.g., clay pots vs. aluminum pots and covered pots vs. uncovered pots). A controlled laboratory does not represent normal cooking conditions of stoves in the field. Efficiency can be defined in many ways depending on the inclusion or exclusion of moisture (water vapor) in the fuel. Higher boiling efficiencies do not necessarily mean fuelwood savings. The energy needed to boil water is not the same as that required to cook meals; thus the stove's efficiency with boiling water is different from the cooking efficiency measure.

The critical objection to boiling water tests is the fact that the tests do not give precise cooking efficiencies. Bialy (1981) showed that despite higher efficiencies for some improved stoves, traditional stoves used less fuel for boiling water than did the improved stove. The improved stove could still be more efficient than the traditional stove, but if changes are made in stove design (such as a three-hole improved stove replacing a two-hole traditional stove), the new stove could use more fuel than the old stove. The dilemma of comparing unequals (a two-hole vs. a three-hole stove) cannot be resolved by changing testing procedures as long as different stove designs are introduced.

Another major problem is using water tests for showing cooking fuel needs. Water tests are used by technicians because WBTs are less easily influenced by a cook's behavior than are CCTs or KPTs. However, water test efficiencies are not meant to give accurate cooking efficiencies. For these reasons, cooking tests are also used by most stove designers.

CONTROLLED COOKING TESTS

A cooking test measures stove efficiency when cooking a "typical" meal. As with the WBTs, CCTs are usually highly controlled in a laboratory. CCTs use representative meals for various regions or cultures within a country. Siwatibau (1981) documented a good example of well-designed traditional meals that could be used to calculate average stove efficiencies under typical Fijian cooking conditions. In addition to traditional meal designs, the experiments incorporated strict measurement, timing, and equipment guidelines.

Siwatibau (1981) developed an efficiency index that relates efficiencies of different stove models to a particular stove type. For example, Siwatibau's efficiency index (EI) related calories expended by a modified Ghanaian oven divided by calories expended by a cooker. Thus the index is a relative measure used for a particular set of experiments conducted under similar conditions. This combination of indexing and strict meal preparation procedures may produce more realistic measurements for comparing various stove types (e.g., wood to charcoal to kerosene to gas). However, the tests must be strictly monitored to make the results comparable with different experiments.

KITCHEN PERFORMANCE TESTS

The KPT estimates the efficiency of a new or traditional stove in an actual household rather than in a laboratory. This test allows household cooks to use the stove with their regular cooking methods and meals. The test is a realistic estimate of how much wood or other fuel is used by a stove under normal cooking conditions. However, because cooking methods and meals differ within and among villages, the results of the KPT cannot be compared as easily as results from the WBT or CCT.

Equations for Stove Efficiency Tests

Even with the problems in measuring stove efficiency, it is still useful to have relative comparisons of efficiency levels for stoves. Clear test procedures can be found in VITA (1983); since this manual will not try to improve upon the VITA publication, only brief statements explain the equations used in the various test procedures. All energy technicians should follow the VITA procedures when making the tests. Only WBT and CCT equations are given.

WATER BOILING TEST EQUATION

The general procedure used in estimating water boiling (thermal) efficiency is to compare the energy transferred to boiling water at a given temperature and atmospheric pressure with the energy (fuel) used in boiling the water. To conduct accurate tests, testing conditions must be recorded and standardized procedures followed. It is useful to run from five to ten tests to find ranges. In measuring the energy used in the fuel, it is also important, particularly with biomass fuels (wood, charcoal, or crop residues), to account for the unburned fuel that remains after the water boils.

A simplified equation for measuring the gross conversion efficiency with WBTs is:

$$\text{Water Boiling Efficiency} = \frac{\text{Mass of Water Heated} \times \text{Specific Heat of Water} \times \text{Temperature Rise in Water}}{\text{Mass of Fuel Used} \times \text{Energy Content of Burned Fuel}} \tag{5.1}$$

$$\frac{(\text{kg})\,(\text{MJ}/{}^\circ\text{C}\cdot\text{kg})\,({}^\circ\text{C})}{(\text{kg})\,(\text{MJ/kg})} \quad \text{or} \quad \frac{(\text{lb})\,(\text{BTU}/{}^\circ\text{F}\cdot\text{lb})\,({}^\circ\text{F})}{(\text{lb})\,(\text{BTU/lb})}$$

However, the full equation in the VITA report should be used. It is important to keep the same fuel type (wood species or crop residue) and container for all experiments.

CONTROLLED COOKING TEST EQUATION

The CCT procedure is more complex than the WBT procedure. In the CCT, precisely measured meals and similar cooking methods must be followed. The basic efficiency is calculated as:

$$\text{Controlled Cooking Efficiency} = \frac{\text{Total Energy Absorbed by Food in Cooking}}{\text{Fuel Input Energy}} \tag{5.2}$$

$$= \frac{\text{Total Weight of Cooked Food} \times \text{Energy Content of Cooked Food}}{\text{Weight of Fuel} \times \text{Energy Content of Fuel}}$$

$$\frac{(\text{kg})\,(\text{MJ/kg})}{(\text{kg})\,(\text{MJ/kg mcwb})} \quad \text{or} \quad \frac{(\text{lb})\,(\text{BTU/lb})}{(\text{lb})\,(\text{BTU/lb mcwb})}$$

Remember that the weight of the "used" fuel includes used minus partially burned or charcoaled portions of the fuel.

KITCHEN PERFORMANCE TESTS

The efficiency formula for the KPT test is similar to the CCT, except the cooked meals are not predetermined. However, data on each meal and household are precisely recorded by an observer during the KPT.

Stove Efficiencies

In reality six different types of efficiencies can be measured for any stove. These are the combustion efficiency, heat transfer efficiency, pan efficiency, control efficiency, cooking efficiency, and stove efficiency (Prasad 1982). The stove or final efficiency is the first five efficiencies multiplied together. These efficiencies are:

$$\text{Combustion Efficiency} = \frac{\text{Energy Generated by Combustion}}{\text{Input Energy of Fuel}} = \frac{\text{Consumed Energy} - \text{Unburned Losses}}{\text{Input Energy of Fuel}} \qquad (5.3)$$

$$\text{Heat Transfer Efficiency} = \frac{\text{Gross Energy into Pan}}{\text{General Energy}} = \frac{\text{Generated Energy} - \text{Stove Loss}}{\text{General Energy}} \qquad (5.4)$$

$$\text{Pan Efficiency} = \frac{\text{Net Energy into Pan}}{\text{Gross Energy Input}} = \frac{\text{Gross Input} - \text{Pan Surface Loss}}{\text{Gross Energy Input}} \qquad (5.5)$$

$$\text{Control Efficiency} = \frac{\text{Energy Absorbed in the Food Mix}}{\text{Net Energy into Pan}} = \frac{\text{Net Energy} - \text{Evaporation}}{\text{Net Energy into Pan}} \qquad (5.6)$$

$$\text{Overall Cooking Efficiency}^{*} = \frac{\text{Energy Absorbed into Food Mix}}{\text{Input Energy of Fuel}} = \text{Equation 5.3 X 5.4 X 5.5} \qquad (5.7)$$

$$\text{Stove Efficiency} = \text{Equation 5.6 X 5.7} \qquad (5.8)$$

Example:

If average conversion efficiencies for a fuel and the average amount of energy used for cooking are known, the amount of required fuel can be calculated. First, the input (received) energy is estimated:

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[*] Overall cooking efficiency used for CCT and KPT.

$$\text{Input Energy Needed} = \frac{\text{Output Heat Produced to Perform a Task}}{\text{Stove Combustion (Gross) Efficiency}}$$

$$\text{MJ/0.xx or BTU/0.xx} = \text{MJ or BTU}$$

The amount of fuel used by the stove to actually deliver the desired usable energy becomes:

$$\text{Fuel Used at Given Moisture Content} = \frac{\text{Input Energy Needed}}{\text{Energy Content per Volume Fuel at Given Moisture Content}}$$

$$\frac{\text{MJ}}{\text{MJ/kg}} \text{ or } \frac{\text{BTU}}{\text{BTU/lb}} = \text{(od kg or kg mcwb) or (od lb or lb mcwb)}$$

As with fuel assessments, it is important in the above equation to use the correct energy content with a fuel's given moisture content—oven dried, air dried, or green basis. These simple methods naturally need refinement when determining precise domestic cooking energy demands and uses for a given stove or fuel.

Suppose we have two stoves, a one-pot metal and a two-pot mud stove. The overall conversion efficiencies in the field are about 10 percent for the metal and only 5 percent for the heavy mud stove. Assuming we need 2 MJ/day of usable energy to cook daily meals, with wood at 15 percent mcwb, the daily input energy required and the fuelwood needs for both types of stoves can be estimated as follows:

Metal Stove

$$\text{Input Energy Needs (MJ)} = \frac{\text{2 MJ/day}}{0.10}$$

$$= \text{20 MJ/day}$$

$$\text{Fuelwood Needs} = \frac{\text{20 MJ/day}}{\text{18 MJ/kg at 15\% mcwb}}$$

$$= \text{1.11 kg/day at 15\% mcwb}$$

Mud Stove

$$\text{Input Energy Needs} = \frac{\text{2 MJ/day}}{0.05}$$

$$= \text{40 MJ/day}$$

$$\text{Fuelwood Needs} = \frac{\text{40 MJ/day}}{\text{18 MJ/kg at 15\% mcwb}}$$

$$= \text{2.22 kg/day at 15\% mcwb}$$

Using these assumptions, the lower overall efficiency of the mud stove has doubled fuelwood needs.

Efficiencies versus Fuel Economy

Although the efficiency measure is important in estimating fuel use, as mentioned earlier a higher stove efficiency does not necessarily mean households will save fuel. French (1984) in Africa and Bialy (1981) in Sri Lanka have shown that improved stoves do not always save fuel. We need to follow these efficiency tests with actual fuel-use data collected during at least six months to a year to determine if cooks really save fuel with the improved stoves. Fuel-use data, gathered by simply weighing the amount of fuel used, must be calculated rather than using the cook's recall.

Even though fuel may not be saved with an improved stove, the stove may be more efficient than an open fire or a traditional umu (lovo). For instance, the woman may cook food longer with a better stove and thus improve family nutrition. A stove project analyst should consider the fuel uses and cooking habits that change or do not change before deciding if a new stove should be introduced in an area. Active participation of women cooks, artisans, and extension workers is needed for a successful program.

Stove Data

Much has been written about stoves in developing countries (Foley and Moss 1983, Manibog 1984) so we will not examine design types. Instead, conversion efficiencies will be given for various stoves. Again, it is critical to warn that efficiencies do not necessarily reveal the amount of fuel used. Remember also that a comparison of different stove types—charcoal, kerosene, or gas versus wood—may also compare different stove designs—one-pot versus two-pot.

Data on stove efficiencies from various countries are reported in Table 5.1. Most are WBT or CCT efficiencies, but sometimes the type of test procedure was not included. Wood stove efficiencies in Fiji are consistently lower (3–10 percent range) than stove efficiencies in the Sri Lanka data (14–23 percent range). The Fijian data may represent cooking efficiency values while the Sri Lanka data probably give water boiling test results, which are often higher than CCT results. In comparing efficiencies across fuel types, efficiencies are ranked from approximately the lowest to the highest from the top to the bottom of the table: wood to kerosene to charcoal to natural gas. Interestingly, this order of fuels is probably the same order used by

Table 5.1. Estimated WBT or CCT Efficiencies of Stoves Used in Pacific/Asia Region

Type of Stove	Efficiency (%)	Country of Data
Wood		
Open fire	5–10	Fiji[a]
3-stones open fire	14–17	Sri Lanka[b]
Indian chula (chimney)	4–6	Fiji[a]
Mud stove without chula (2-pot)	14–23	Sri Lanka[b]
Lovo (ground oven)	3–5	Fiji[a]
Metal	10–25	
Charcoal (metal, lined)	25–35	
Kerosene		
Hong Kong (10-wick)	15–29	Fiji[a]
	37.7	New Zealand[a]
Swedish primus (wood)	30–57	Fiji[a]
	27.5	New Zealand[a]
Gas	55–65	

Sources: [a]Siwatibau (1981, p. 41).
[b]Bialy (1981).

the households as their incomes increase, e.g., wood stoves or open fires are used by subsistence or low-income households whereas high-income households may use kerosene or liquefied petroleum gas (LPG) (Rizer 1985, Siwatibau 1981). Rizer showed that a greater percentage of the highest income groups in his Ponape study used kerosene for cooking whereas only a small percentage of the lowest income groups used kerosene.

Stove Economics

A comparison of stove costs in Ponape was made in the Energy Mission Reports, Ponape (1982), in 1981 values. Table 5.2 shows the relative costs of electric, wood, and charcoal stoves. According to these figures, wood is the cheapest fuel per MJ (BTU) of energy delivered (usable energy) followed by charcoal, then electricity. Unfortunately, the types of stove design are not given so fair comparisons may not exist.

Interestingly, even though an electric stove has the highest appliance efficiency (70 percent), and wood the lowest efficiency (20

Table 5.2. **Comparative Fuel Costs of Cooking with Electricity and Solid Fuels in Ponape (1981 U.S. Dollars)**

		Average Efficiency of Appliance	Energy Content[a]		Cost per Unit of Energy		Proportion of Cost of
Fuel	Price per Unit	(%)	MJ per Unit	BTU per Unit[b]	c/MJ	c/BTU	Electricity
Electricity	23.5c/kWh	70	3.6	3,400 BTU/kWh	9.33	0.0069	1
Wood[c]	$25/MT at 40% mcwb	20	10.9 MJ/kg	4,700 BTU/lb	1.15	0.0012	0.12
Charcoal[c]	$200/MT	30	27 MJ/kg	12,000 BTU/lb	2.23	0.0026	0.24

Source: Energy Mission Reports, Ponape, Appendix 4.41 (1982).

[a] Values in this and following tables represent averages with possible ranges of ± 15 percent.

[b] Adjusted for BTU conversion.

[c] In slow combustion stove.

percent), electricity is still far more expensive than wood on a delivered energy basis (i.e., after adjusting for combustion efficiency). Given that electricity production is extremely inefficient (10–20 percent), these data suggest electric stoves are not only uneconomical but also a poor use of high-quality energy, unless electricity production is cheap for the country and wood fuels are scarce. The introduction of improved wood stoves and charcoal stoves could be a more attractive and better use of energy fuels in a country with adequate wood supplies than use of electric stoves when electricity is unreliable, as on outer islands.

CHARCOAL KILNS

Because charcoal is a clean household and industrial fuel, charcoal programs are popular throughout the Pacific Basin, e.g., Papua New Guinea (Gamser and Harwood 1982), Tonga (Newcombe 1981), Fiji (Newcombe 1981), and the Philippines (Hyman 1981). Charcoal's major attractions for development and energy planners are: (1) a wide range of scale economics (kiln sizes) for charcoal production; (2) production of a dense, clean fuel which burns uniformly, (3) a fuel with lower per unit transport costs than wood; (4) a simple, mobile production process that is easily accomplished with local labor and materials; and (5) fewer but different pollutants than wood, thereby reducing smoke exposure for the cooks. However, if poor-quality charcoal is made it will break into fines during transport and must be briquetted.

Charcoal Production and Technologies

Charcoal is made by burning wood in a slow-burning, oxygen-poor environment. The final product is 70–90 percent fixed carbon, 7–20 percent volatiles, 0.10–10.0 percent ash, and 0.02–0.03 percent sulfur (Hyman 1981). The energy content of charcoal ranges from 28–33 MJ/kg (16,000–20,000 BTU/lb).

Traditionally charcoal is produced in soil pits or earth-covered mounds. Newer technologies utilize oil drums (the Philippine and Tongan oil drum methods), portable metal kilns, and stationary community-sized kilns or retorts. The basic differences in the methods are charcoal quality and charcoal output due to differences in equipment size.

The **Philippine oil drum method** keeps the oil drum vertical during charcoaling. The top and bottom of the drum become lids that control air and wood intake. In the **Tongan method**, the oil drum rests horizontally during the charcoal process. Slits are cut vertically in the sides of the drum to control air supply and feedstock input. A simple design description is found in Gamser and Harwood (1982). Both drum methods are small-scale technologies, using 200-liter drums. On average, these drum methods are capable of producing 12–15 kg of charcoal per day, assuming that each firing requires one day, 2.5–3 MT of coconut shells are used each week, and the kilns are fired five days a week (Energy Mission Reports 1982, Gamser and Harwood 1982). According to Gamser and Harwood, the Philippine drum method is better than the Tongan one but both methods have the advantages of simplicity, mobility, and limited training requirements and material needs.

Charcoal kilns and retorts are large-scale methods of charcoal production. These methods require more capital, training, and materials than the drum methods. A variety of commercial kilns exist, but the most well-known and preferred kiln in the Pacific is manufactured by the Tropical Products Institute (TPI). The kilns range in sizes larger than the drums, produce more charcoal, and have higher capital costs and feedstock needs. An area must have a large charcoal demand for such kilns to be economically viable, given their production levels and capital costs. In Fiji, a 7m^3 TPI kiln uses 2.0–2.5 MT of solid sawmill residue (not sawdust) per cycle and yields 300–400 kg of charcoal per cycle depending upon loading. Cycles last anywhere from 12 hours to two days (Gamser and Harwood 1982; Energy Mission Reports, Fiji 1982). According to Gamser and Harwood (1982), kilns are better than retorts as kilns have longer lives, lower capital equipment costs, and lower per unit charcoal production costs as compared with retorts.

Measuring Charcoal Kiln Efficiency

The conversion efficiency of charcoal production depends upon the original feedstock and equipment design. As wood is concentrated into charcoal, energy is lost in the conversion process due to partial burning of the wood and heat escaping to the atmosphere. The actual conversion efficiency for any charcoal process can be found using the following equation:

$$\text{Gross Efficiency} = \frac{\text{Usable Energy in Charcoal}}{\text{Feedstock Input Energy}}$$

$$= \frac{\text{Per Unit Energy Content of Charcoal} \times \text{Amount of Charcoal Produced}}{\text{Per Unit Energy Content of Feedstock at Given Moisture Content} \times \text{Amount of Feedstock at Given Moisture Content}} \qquad (5.9)$$

$$\frac{(\text{MJ/kg})\ (\text{kg})}{(\text{MJ/kg mcwb})\ (\text{kg mcwb})} \text{ or } \frac{(\text{BTU/t})\ (\text{t})}{(\text{BTU/t mcwb})\ (\text{t mcwb})}$$

The equation says the gross efficiency of conversion is the ratio of the energy content in charcoal produced by conversion to the energy potential in the feedstock. As with all fuels, the energy content of the fuel must be for the given fuel's moisture content (mcwb or oven-dry basis).

Charcoal Data

An important distinction with charcoal production is its per unit energy content, as compared with wood, and its conversion efficiency. The per volume energy content of charcoal is usually around 30 MJ per kilogram at 5 percent moisture content as compared with 12 MJ per kilogram for wood at 45 percent moisture content wet basis and 20 MJ per kilogram for wood at 0 percent moisture content wet basis (Energy Mission Reports 1982). However, converting wood fuels to charcoal creates net energy losses anywhere between 30–84 percent (French 1979). Thus, 30–84 percent of the wood's net energy may be lost in the final product, charcoal. This means that charcoal may have higher per volume energy values than wood, but more total energy can be produced by simply burning wood rather than by converting it first to charcoal and then burning the charcoal. This relationship depends on the conversion efficiencies of the production process and end uses (stoves).

One precaution in working efficiency estimates is to also consider the conversion efficiency of the end use when calculating charcoal and feedstock demand. For instance, if a charcoal stove needs 100 MJ per day and has an average 20 percent stove efficiency (Gamser and Harwood 1982), then the daily heat input needed for the stove is:

$$500 \text{ MJ} = 100 \text{ MJ} \div 0.20$$

If coconut shells are used as the feedstock with a conversion efficiency in drums of 15 percent, and air-dried coconut shells have 13.7 MJ per kilogram at 30 percent mcwb, then coconut shell needs are:

$$\text{Coconut Shell Needs} = \frac{500\ \text{MJ/day}}{(0.15)\ (13.7\ \text{MJ/kg mcwb})} = 243\ \text{kg at 30\% mcwb}$$

Charcoal Production Economics

Since use of wood or coconut shells for charcoal production is encouraged in the Pacific, some average cost estimates are helpful for interested communities or individuals. The example used in this section is based on production using the Philippine kiln method (200-liter drums) in Kiribati (Energy Mission Reports, Kiribati 1982).

The basic assumptions and resource and energy assessments are given below, with Table 5.3 showing a financial average cost analysis of charcoal production.

Example:

The basic assumptions for charcoal production in Kiribati are:

- 200-liter drums will be used with the Philippine kiln method
- Ten drums will be used, with each drum lasting approximately six months
- One laborer will manage 10 drums
- Coconut shells will be used as feedstock; 2.5–3 MT shells/week (30% mcwb)
- Charcoal production is 12 kg/day, 60 kg/week per drum
- Annual production is 50 weeks

The calculations for the resource assessment are

$$\begin{aligned}\text{Annual Charcoal Production} &= \text{3.0 MT mcwb shells} \times \text{20\% Charcoal Conversion Factor} \times \text{50 weeks}\\ &= \text{30 MT mcwb/yr (27 t mcwb/yr)}\end{aligned}$$

The calculations for the energy assessment are:

$$\begin{aligned}\text{Annual Charcoal Input Energy Potential} &= \text{(30 MT mcwb/yr) (30,000 MJ/MT mcwb)} = \text{900,000 MJ/yr}\\ &\ \text{(27 t mcwb/yr) (26 MMBTU/t mcwb)} = \text{702 MMBTU/yr}\end{aligned}$$

According to the energy assessment, charcoal production of 30 MT per year (27 t/yr) will provide 900,000 MJ or 702 MMBTU annually in input energy potential.

A break-even financial analysis of the charcoal kilns is made in Table 5.3. Annual average costs are found for capital and operating and maintenance (O+M) cost components, then a retail margin is

Table 5.3. A Break-even Analysis of Annual Average Costs for Charcoal Kilns in Kiribati (1981 Australian Dollars)

Financial Cost Component	Annual Average Cost (A$/yr)	Cost per Unit Charcoal (A$/MT)	Cost per Input Energy (A$/MJ)
Capital charges[a]			
Tools (screen, stapler scales)	60	na	na
Capital cost			
10 kilns ($10/kiln, 6-month life)	200	na	na
Operation/maintenance			
Coconut shells ($10/MT)	1,500	na	na
Labor (A$/day)	1,250	na	na
Tools (snips, chisels)	30	na	na
Bagging	750	na	na
Total without transport	3,790	126.00	0.04
Transport costs			
To port ($15/MT)	450	na	na
To Tarawa ($55/MT)	1,650	na	na
Total wholesale cost	5,890	196.00	0.07
Retail margin (35%)	2,060		
Total retail cost	7,950	265.00	0.09
Break-even price ($265/MT)	7,950	265.00	0.09

Source: Costs are adapted from Energy Mission Reports, Kiribati, Appendix 4.6.1 (1982). Altered costs are tool charges plus O+M costs.

[a] Capital charge: using a 3-year life and a 10 percent interest rate. Only capital charges are used on tools, as kilns need to be purchased every six months.

added to derive the break-even price (A$265/MT) that is needed to cover retail costs. The wholesale break-even price for distributors at Tarawa would be A$196/MT, and the break-even price for charcoal production, excluding transport costs, is A$126/MT. A major proportion of wholesale price is transport costs (36 percent). Interestingly, if charcoal producers buy coconut shells from a local market, shell costs, followed by labor costs, are the highest portion of total charcoal production costs.

In conclusion, charcoal kilns have important advantages for rural areas in the use of local materials and labor, ease of production, and utilization of waste resources (e.g., coconut shells). Given the ability of small landowners to easily use this technology and given an urban/rural demand, charcoal production could provide a high-quality domestic cooking fuel for middle- and low-income users. However, good quality charcoal must be produced and coconut shells will often produce friable charcoal that easily breaks up into fines. Thus, briquetting or the use of better biomass feedstocks may be needed in the Pacific to make charcoal production a good fuel alternative.

BIOGAS DIGESTORS

During the seventies and on into the eighties, biogas digestors have been promoted strongly as an important technology for meeting rural energy needs. Biogas digestors can bring improvements in both energy quality and services. Despite the enthusiasm for digestors, the failure rate for digestors in many Pacific island countries is quite high. Thus it is important to compare the obvious benefits of digestors with their apparent shortcomings.

Digestors can be directly beneficial because they: (1) use feedstocks that are commonly society's waste products, e.g., crop residues and animal or human wastes; (2) produce waste products (sludge) that can be used as a fertilizer for soil improvement; (3) provide important public health and sanitation benefits; and (4) produce gas for cooking, lighting, and heating. Indirect environmental benefits are reduced deforestation if biogas substitutes for wood fuel and more sanitary waste disposal conditions if animal or human wastes are used. If digestors are manufactured locally, other benefits can be increased local employment and use of local materials such as cement or bricks. If biogas replaces kerosene for lighting or cooking, foreign exchange fuel savings may also occur but probably will be offset by foreign exchange needs of imported digestor equipment.

Unfortunately, the failure rate of biogas digestors in the Pacific has been quite high. The failures appear to result from a combination of social, technical, and economic problems. One important consideration, which was often overlooked in past projects, is the human reluctance to collect and handle animal or human waste and lack of training for maintaining and repairing the digestors. A community or multifamily digestor may require social cooperation that simply may be unfeasible. Wastes such as dung or crop residues may already be important as a free energy source for low-income groups; by introducing digestors, the group's access to that resource may be in jeopardy. If cooperation for raw materials (e.g., residues, bricks, cement, or water) extends beyond community boundaries, a separate set of social and economic limits may exist (Bajracharya 1982). Projects that require a change in social structure usually fail unless the need and priority are recognized by villagers.

In addition to social considerations, technical and economic problems have slowed the acceptance of biogas digestors. Technical problems include a lack of trained operators, poor equipment design or materials, and failure to regularly feed the digestor. Although a digestor is a relatively simple technology, it requires certain operating skills and quality construction materials. A lack of wastes may also cause failure. If no market exists for the primary product, e.g., pigs, cows or crops, then the waste supply to fuel the digestor cannot be assured.

Competition for waste resources includes an individual family's needs for mulch, fertilizer, or domestic cooking. Because of the high failure rate of digestors, it is important that technicians and extension agents actively participate with villagers or households to assess the village or individual needs and the appropriateness of the technology to those needs. Two methods for assessing needs are *appropriateness* indices (Santerre and Smith 1982) and participatory action research (Bajracharya 1982).

Biogas Digestor Technology

Biogas is produced during an aerobic digestion of liquefied organic material. Common feedstocks include cow and pig manure, crop residues, human wastes, and organic industrial sludge. Technically, biogas digestion is a three-step process involving (1) hydrolysis of cellulose into glucose, (2) glucose conversion into fatty acids, alcohol, and carbon dioxide (CO_2) through bacteria fermentation, and (3) conversion of these fatty acids and alcohol into methane (CH_4) and carbon dioxide by methanogenic bacteria.

Biogas digestors are classified by the type of gas-collecting lid (dome) or by the type of construction material. Three common designs are floating dome, fixed dome, and bag digestors. Santerre and Smith (1982) provide a thorough description of construction material, labor, and feedstock requirements for fixed and floating dome digestors that are typically found in the Pacific. ESCAP (1981) presents detailed information on design differences and advantages. Such technological information is not the purpose of this manual.

Biogas Digestor Equations

A digestor fuel and energy assessment requires several estimates: biogas capacity needed for end-use demand, usable energy produced (output energy supplied by a digestor), digestor's conversion efficiency, and necessary feedstock supply. If sizing a digestor to the energy demands of a household or community, the calculations are made from end-use demand to feedstock supply requirement. In contrast, if the feedstock supply exists, as with a commercial piggery or palm oil industry, the digestor will be sized from a supply estimate.

Estimating the biogas demand depends on the desired end uses. Biogas can be used for cooking, lighting, refrigeration, heating, and in dual-fuel engines. The basic equation for estimating biogas capacity demand for cooking and lighting purposes can be written as follows:

$$\begin{array}{l}\text{Annual Biogas}\\ \text{Capacity Needed}\\ (\text{ft}^3/\text{yr})\end{array} = \begin{array}{l}\text{Annual}\\ \text{Cooking}\\ \text{Needs}\\ (\text{ft}^3/\text{yr})\end{array} + \begin{array}{l}\text{Annual}\\ \text{Lighting}\\ \text{Needs}\\ (\text{ft}^3/\text{yr})\end{array} + \begin{array}{l}\text{Annual}\\ \text{Other}\\ \text{Needs}\\ (\text{ft}^3/\text{yr})\end{array} \tag{5.10}$$

$$\begin{array}{l}\text{Annual Cooking}\\ \text{and Lighting}\\ \text{Needs}\end{array} = \left(\begin{array}{l}\text{Persons in}\\ \text{Household}\\ (\#)\end{array} \times \begin{array}{l}\text{Daily per Capita}\\ \text{Gas Use}\\ (\text{ft}^3/\text{person}\cdot\text{day})\end{array} \times \begin{array}{l}365\\ \text{Days}\end{array}\right) + \left(\begin{array}{l}\text{Lamps}\\ (\#)\end{array} \times \begin{array}{l}\text{Rated Capacity of}\\ \text{Lamps per Hour}\\ (\text{ft}^3/\text{hr})\end{array} \times \begin{array}{l}\text{Hours}\\ \text{per Day}\\ (\text{hr/day})\end{array}\right)$$

After demand (right side of Equation 5.10) is calculated, the digestor size (capacity) required to meet this demand can be estimated. The biogas capacity is usually expressed by the volume of gas produced from the digestor. The volume of gas produced is a function of the digestor volume (V), annual seasonal production rates during a yearly cycle, and downtime. Annual usable energy can be estimated by multiplying the gas volume by energy content per unit of gas, and conversion efficiency. Seasonal variation in gas production is important to energy output in most locations except the tropical lowlands. For example, during colder months in the highlands gas production will drop if the digestor temperature decreases significantly. A seasonal variation adjustment can be made in the utilization rate by taking an average annual rate for varying time periods. The actual equation for estimating annual usable energy is:

$$\begin{array}{lllllll} \text{Annual Usable} & = & \text{Daily Maximum} & \times & \text{Days} & \times & \text{Average Seasonal} \\ \text{Energy} & & \text{Rated Capacity} & & \text{per} & & \text{Production} \\ (\text{MJ/yr}) & & (\text{m}^3/\text{day}) & & \text{Year} & & (\text{High, Low}) \\ (\text{BTU/yr}) & & (\text{ft}^3/\text{day}) & & (365) & & [(\%\text{H} + \%\text{L})/2] \end{array}$$

$$\begin{array}{llll} \times & \text{Annual} & \times & \text{Energy Content} \\ & \text{Downtime} & & \text{per Unit Gas} \\ & (0.\text{xx}) & & (\text{MJ/m}^3) \\ & & & (\text{BTU/ft}^3) \end{array} \qquad (5.11)$$

where H and L represent the low production rate in season 1 and the high production rate in season 2.

The daily **rated capacity** (V) is the digestor's maximum gas production capability per day. The seasonal production or utilization rate is the percentage of total rated capacity the digestor usually provides. The rate can be a weighted average of seasons (percentage of H plus percentage of L divided by 2 if equal length of seasons) to reflect seasonal variation. If downtime is not included in the average digestor production rate, it is another factor to be included as in Equation 5.11. The actual energy content of the gas produced is the final variable in the equation.

The daily rated capacity (V) is derived from the equation:

$$\begin{array}{llll} \text{V} = \dfrac{\text{Daily Feedstock Input}}{\text{Solid/Water Mixture Density}} & \times & \text{Retention Time} & (5.12) \\ \dfrac{\text{kg/day}}{\text{kg/l}} \text{ or } \dfrac{\text{lb/day}}{\text{lb/ft}^3} & & (\text{days}) & \end{array}$$

To estimate the feedstock input, the following equation is used:

$$\begin{array}{lllllll} \text{Annual} & = & \text{Feedstock Input Energy} & \times & \text{Gross Efficiency} & & \\ \text{Usable} & & & & & & \\ \text{Energy} & = & \text{Annual Feedstock} & \times & \text{Energy Content} & \times & \text{Gross} \\ & & \text{Volume} & & \text{per Volume} & & \text{Efficiency} \\ & & (\text{kg/yr}) & & (\text{MJ/kg}) & & (0.\text{xx}) \\ & & (\text{lb/yr}) & & (\text{BTU/lb}) & & \end{array} \qquad (5.13)$$

By knowing the gross efficiency and annual usable energy demand, the required feedstock supply can be estimated using the above equation.

Biogas Digestor Data

Several characteristics are important to digestor success. The **organic matter to water ratio** is the ratio of organic matter such as dung, waste, or sludge to water. Most ratios are given for dung/water mixtures, with ratios of 1:1 (Bajracharya 1982), 1:3 and 1:5 commonly being used. The precise ratio should be determined by the user according to feedstock type.

The **carbon to nitrogen ratio** is important for maintaining the proper chemical environment for the bacterial growth. Bajracharya (1982) suggests a ratio of 25–30:1.

Methane bacteria work best in a neutral or slightly alkaline environment for growth and reproduction, so **pH regulation** is important. The best pH range for a digestor is between 6.5–7.5, although gas production is possible between 5–8 pH.

Retention time, the amount of time the organic matter/water mixture is retained in the digestor, affects gas production. The average cold-climate retention time for a continuous process digestor is 30 to 45 days. A lower retention time of 15 to 25 days is possible in warm climates.

A specific **temperature range** must be maintained within the digestor for bacteria to break down the material. The lower end of the temperature range is approximately 37°F (5°C), and the upper end goes above ambient air temperatures in the Pacific. A mesophilic (middle temperature) range of 20°–45°C is typical for digestors. Gas production increases at higher temperatures (thermophilic range), but an additional heat source is normally needed; it is important to assess whether the amount of additional energy produced at higher temperatures is worth the additional energy input. Below 20°C, gas production decreases rapidly.

A continuous process digestor, in contrast with a batch process, requires **daily feeding** even after the digestor is filled. When supply estimates are calculated, it is important to know both the feedstock quantity required (start-up supply) to fill the digestor and the amount of additional feedstock needed daily. The feedstock supply estimation procedure is outlined in the set of equations.

Each of these technical considerations contributes to a well-run and well-planned digestor. But social, cultural, and economic considerations also need to be considered.

Presenting only general gas production data can be misleading since a wide variety of sizes, designs, and end uses exists for biogas digestors. As with other technologies, a gross conversion efficiency is as much a function of the operations and maintenance as of design and size. A typical gross efficiency range for digestors is 20–35 percent, but the efficiency of converting an organic feedstock into gas is only part of the overall energy system's efficiency. Gas lamps, motors, stoves, and refrigerators all have their own efficiencies. Biogas capacity demand calculations must incorporate these gross efficiencies in estimating lamp gas or stove gas use. Good references on biogas digestor sizes, production capabilities, and material needs are Santerre and Smith (1982), Bajracharya (1982), Siwatibau (1981), and ESCAP (1981).

Biogas Digestor Economics

As mentioned earlier in this section, the economics of digestors are often tied to the profitably sized unit of the primary product, such as pigs or palm oil. Adapting an example from a palm oil mill owned by the Solomon Islands Plantations, Ltd. (Energy Mission Reports, Solomon Islands, Appendix 4.2.9, 1982), a financial, annual average cost analysis is shown using palm oil mill effluent (POME).

Example:

The fuel production assumptions for a palm oil sludge biogas plant in the Solomon Islands are:

- 85,000 MT of fruit bunches per year
- 300 kg POME per MT of fruit bunches

The biogas digestor assumptions are:

- Using a 3,400 m^3 digestor
- 28.3 m^3 biogas/m^3 POME
- 300 days of gas production per year
- Gas quality: 54.6–69.7 percent gas in gas mixture (10-day retention)
- 22.5 MJ/m^3 gas (600 BTU/ft^3 gas)
- Digestor efficiency is 0.80

The generator assumptions are:

- The gas compression engine's maximum electricity production is 1.53 GWh
- The plant utilization factor is 85 percent
- The auxiliary energy use is 0.08 GWh

The calculations for the resource assessment are:

$$\begin{aligned}\text{Annual POME Potential} &= (300\ \text{kg/MT})\ (85{,}000\ \text{MT/yr}) \\ &= 25{,}500{,}000\ \text{kg/yr} = 25{,}500\ \text{m}^3\text{/yr}\end{aligned}$$

The calculations for the energy assessment are:

Annual Gas Production = (28.3 m^3/m^3 POME) (25,500 m^3/yr)
= 721,650 m^3/yr

Annual Gas Input Energy Potential = (721,650 m^3/yr) (22.5 MJ/m^3)
= 16.24 X 10^9 J/yr

Usable Gas Energy Potential = (16.24 X 10^9 J/yr) (0.80)
= 13.0 X 10^9 J/yr
= 4.67 GWh/yr (using 1 J = 2.78 c 10^{-7} kWh)

Delivered Gas Energy Potential from Generator = 4.67 GWh/yr (0.85)
= 3.97 GWh/yr

Maximum Delivered Electricity from Generator = (1.53 GWh/yr) (0.85)
= 1.30 GWh/yr

Actual Maximum Delivered Electricity = 1.30 GWh/yr – 0.08 GWh (auxiliary use)
= 1.22 GWh/yr

Excess Energy from POME Gas = 3.97 GWh/yr – 1.30 GWh/yr
= 2.67 GWh/yr excess potential

In the Solomon Islands resource and energy assessment, the usable energy in the biogas is 4.67 GWh after leaving the digestor. When adjusting for an 85 percent gross efficiency in the biogas-fueled generator, the actual electricity-generation capability from the POME gas is 3.97 GWh. Knowing that the gas generator has a maximum 1.53 GWh/yr production and an 85 percent plant factor, the electricity uses (fans or exchanges) reduce maximum salable electricity to 1.22 GWh/yr. Given a delivered gas potential of 3.97 GWh and a maximum delivered potential of 1.3 GWh from the engines, there is an excess energy potential of 2.67 GWh.

Adapting the financial data for the biogas/gas engine system, annual average costs and benefits are shown in Table 5.4. The costs include capital and operating costs for the biogas/generator system; benefits include the potential revenue gained from electricity sales to a grid or to direct users. The capital charge in Table 5.4 possibly underestimates the actual capital expenditure, since capital costs in the Energy Mission Reports, Solomon Islands (1982), appeared to include only the gas compression ignition engines and not the digestor. In

Table 5.4. Annual Average Costs and Benefits of a Palm Oil Sludge Biogas Plant in the Solomon Islands (1981 SI$)

Costs	Annual Average Costs (SI$/yr)	Cost per Unit Energy (SI$/kWh)
Capital charge[a]		
Biogas digestor/gas engines	23,140	na
Operating and maintenance		
Fuel labor (4 X $3,000/yr)	12,000	na
Generator maintenance	19,500	na
Digestor maintenance	8,800	na
Total costs	63,440	0.05
Benefits		
Electricity sales (1.22 GWh, 10¢/kWh)	122,000	0.10
Net benefits	58,560	0.05

Source: Energy Mission Reports, Solomon Islands, Appendix 4.2.2 (1982).

[a] Capital charge for engines (SI$800/kW at 220kW) is $176,000. Charge assumes 10 percent interest rate and 15-year project life.

comparing the net benefits, it is clear that electricity generation from biogas is quite attractive financially at a 5¢/kWh net benefit, half the per unit energy charge for electricity in the Solomon Islands (10¢/kWh). Since this latter electricity price is probably subsidized but the capital costs of the digestor plant are underestimated, the net benefits will probably still favor the palm oil digestor over buying electricity from the grid.

GASIFIER SYSTEMS

Gasification has generated renewed interest primarily because it produces a clean fuel (producer gas), which easily substitutes for many natural gas uses. Although the technology was proven in World War II, recent commercial use has been slow due to operating and fuel supply problems. The clear expected attractions of gasifiers should be balanced by their current operational limitations particularly in the Pacific. Foley and Barnard (1982) aptly stated that the contemporary issue is not to prove that gasification technology works but to identify cases where it is appropriate and actually feasible. At this point, gasifiers should be considered only for pilot projects in the Pacific where trained operators are available.

Producer gas is an attractive fuel because it can be used for providing shaft power (i.e., mechanical energy) as well as direct heat. Although the fuel has a lower calorific value than natural gas, its advantage is that the producer gas has higher LHV than solid fuels such as charcoal, wood, or residues. Since indigenous fuels, such as wood and coconut shells, are used as feedstocks, gasification may displace fossil fuel use, thereby saving some foreign exchange, but capital costs for gasifier equipment may partially offset these savings. Using local raw materials and locally trained operators can be other advantages of gasifiers.

Gasifiers, however, have important drawbacks that must be considered by potential users. Although the Philippines and Brazil have started ambitious programs, widespread commercial use in developing countries generally does not exist (Cruz 1977, Foley and Barnard 1982). The only proven, practical feedstock fuels are wood, coconut shells, and charcoal (Foley and Barnard 1982); crop residues (rice husks) generally are still being tested for field use (Cruz 1977). System success depends on the combination of an adequate, steady fuel supply, appropriate design, and an adequate labor force with proper maintenance and operational skills. The fuel supply and labor skills have generally been the major problems in commercial use in the Pacific islands.

With medium- to large-scale units, gasifiers are inappropriate if laborers are not technically skilled or if repair and maintenance services cannot be provided. Even with small units, trained technicians should manage the system. Gasifiers are potentially explosive and require full-time supervision in the initial years. Foley and Barnard (1982) warn against commercial adoption unless skills are available and maintenance services can be provided. French Polynesia, Saipan, and the Cook Islands have experienced fuel supply problems that have periodically shut down their systems. Thus far widespread commercial industrial use has generally not been successful outside of the Philippines, Brazil, and some developed countries.

Gasification Technology

A gasifier burns fuel in an air-restricted environment, causing partial combustion of the feedstock. The heat produced from partial combustion breaks down the remaining unburned fuel into gases (hydrogen, carbon monoxide, and nitrogen) and residuals (ash and tars).

These hot gases, also referred to as producer gas, are then cleaned and used to produce mechanical energy or direct heat (Foley and Barnard 1982).

Three basic gasifier designs are updraft, downdraft, and fluidized bed. (See SERI 1979 and Reed 1981 for technical descriptions.) Updraft gasifiers are simpler in design than downdraft gasifiers but produce tars and oils that can condense in the unit's cooler areas, causing operating problems. Downdraft gasifiers are designed to eliminate the tar and oil problems. A simple filtering system is needed to clean the gases in downdraft gasifiers. The more recent fluidized bed gasifiers produce uniform temperatures and have higher fuel inputs than the other designs. Such high fuel throughput tends to remove the ash and char with the gas, thereby requiring physical separation and adding to total system costs (Reed 1981, SERI 1979). In contrast to these gasifier designs, hot-air gasifiers made in New Zealand or the United States are excellent and cheap for crop drying (Energy Mission Reports 1982).

Producer gas has a lower heat value (5.9 MJ/m^3) than natural gas (34.8 MJ/m^3) and for this reason is often called low-BTU gas. The gas is used to produce either mechanical energy from shaft power (SP) or steam for direct heat (DH). Shaft-power units use the gas to run engines, whereas direct heat systems burn the gas in boilers, furnaces, or kilns to produce hot-air or steam heat. As shaft-power systems produce electricity, the systems' output is measured in kilowatts or horsepower (HP). Typical units range from 7.5 to 480 kilowatts (10.1 to 643 HP). Direct-heat output is measured in heat production per unit of time, i.e., in megajoules (MJ) or gigajoules (GJ) per hour (or BTU per hour). Such systems range from 0.25–25.0 GJ/hr (0.24–24.0 MMBTU/hr).* In the Philippines, fishermen use small 5–20 HP gas engines fueled by charcoal to run outboard motors (Cruz 1977).

Gasifier Equations

Determining the appropriateness of gasifiers involves knowing the system's conversion efficiency and determining if an adequate and reliable fuel supply exists. As with other conversion systems, the gross efficiency equals the ratio of actual energy produced (usable energy) to the potential energy input from the fuel. Since a gasifier is usually one component in either a shaft-power or direct-heat system, several conversion efficiencies exist.

---

* Conversion factors used are 1 kilowatt = 1.34 horsepower, and 1 gigajoule = 0.95 × 10^6 BTU (Foley and Barnard 1982).

First is a conversion efficiency for the gasifier, i.e., the gasifier's efficiency in converting wood, charcoal, or residues into producer gas. Second are the conversion efficiencies of the engines or boilers that use the gas to produce mechanical power or heat. Each component will waste some energy, so a system's overall conversion efficiency is an accumulation of inefficiencies. As noted earlier, every efficiency is specific for that particular design, size (scale), age, utilization (load) capacity, and feedstock. Estimates using the general equations should be accompanied by such system characteristics.

GASIFIER SYSTEM

The conversion efficiency equation for the gasifier is:

$$\begin{array}{l}\text{Gross}\\ \text{Efficiency}\\ \text{of Gasifier}\end{array} = \frac{\text{Usable Energy Produced}}{\text{Feedstock Input Energy}} \qquad (5.14)$$

$$= \frac{\text{Energy Content of Gas} \times \text{Amount of Gas Produced}}{\text{Energy Content of Fuel} \times \text{Amount of Fuel Used}}$$

$$\frac{(\text{MJ/m}^3)\ (\text{m}^3)}{(\text{MJ/kg})\ (\text{kg})} \quad \text{or} \quad \frac{(\text{BTU/SCF})\ (\text{SCF})}{(\text{BTU/t})\ (\text{t})}$$

The equation to calculate the annual energy produced by the gasifier is:

$$\begin{array}{l}\text{Annual Out-}\\ \text{put Energy}\\ \text{from Gasifier}\end{array} = \begin{array}{l}\text{Potential}\\ \text{Hourly}\\ \text{Gas Rate}\\ (\text{m}^3/\text{hr})\\ (\text{SCF/hr})\end{array} \times \begin{array}{l}\text{Energy}\\ \text{Content}\\ \text{per Unit}\\ \text{Gas}\\ (\text{MJ/m}^3)\\ (\text{BTU/SCF})\end{array} \times \begin{array}{l}\text{Hours}\\ \text{per}\\ \text{Year}\\ (\text{hrs})\end{array} \times \begin{array}{l}\text{Load}\\ \text{Capac-}\\ \text{ity}\\ (\%)\end{array} \times \begin{array}{l}(100 - \%)\\ \text{Downtime}\\ (100 - \%)\end{array} \qquad (5.15)$$

The equation to estimate the annual fuel input energy need for the gasifier only is:

$$\begin{array}{l}\text{Annual Fuel}\\ \text{Input Energy}\end{array} = \frac{\text{Annual Gasifier Output Energy}}{\text{Gasifier Conversion Efficiency}} \qquad (5.16)$$

Equations 5.14, 5.15, and 5.16 are used to find the combustion efficiency, energy output, and fuel demand for the gasifier only. Such characteristics are somewhat misleading because they relate to only part of any conversion system. The gasifier will usually be connected to either a shaft-power or direct-heat system.

GASIFIER/SHAFT-POWER OR GASIFIER/DIRECT-HEAT SYSTEM

The equations to calculate the conversion efficiency for a shaft-power (SP) or direct-heat (DH) gasifier system are:

$$\begin{array}{l}\text{Gross}\\ \text{Efficiency}_{SP}\end{array} = \frac{\text{Output Energy Production of Shaft Power}}{\text{Gas Fuel Input Energy}} \qquad (5.17)$$

$$\frac{(\text{kW})\ (\text{MJ/kW})}{(\text{MJ/m}^3)\ (\text{m}^3)} \text{ or } \frac{(\text{HP/hr})\ (\text{BTU/HP})}{(\text{BTU/SCF})\ (\text{SCF/hr})}$$

$$\begin{array}{l}\text{Gross}\\ \text{Efficiency}_{DH}\end{array} = \frac{\text{Output Energy Production of Direct Heat}}{\text{Gas Fuel Input Energy}} \qquad (5.18)$$

$$\frac{\text{MJ/m}}{(\text{MJ/m}^3)\ (\text{m}^3)} \text{ or } \frac{\text{BTU/m}}{(\text{BTU/SCF})\ (\text{SCF})}$$

$$\begin{array}{l}\text{Annual Output}\\ \text{Energy from}\\ \text{Either System}\\ (\text{kWh/yr})\\ (\text{BTU/yr})\end{array} = \begin{array}{l}\text{Rated Energy}\\ \text{Production}\\ \text{per Hour}\\ (\text{kWh})\\ (\text{BTU/hr})\end{array} \times \begin{array}{l}\text{Hours}\\ \text{per}\\ \text{Year}\\ (\text{hrs/yr})\\ \end{array} \times \begin{array}{l}\text{Utilization}\\ \text{Capacity}\\ (\%)\\ \\ \end{array} \times \begin{array}{l}(100-\%)\\ \text{Downtime}\\ (100-\%)\\ \\ \end{array} \qquad (5.19)$$

The equation to calculate the annual fuel input needs for a shaft-power or direct-heat gasifier system is:

$$\begin{array}{l}\text{Annual Fuel}\\ \text{Input Needs}\\ (\text{MJ/yr})\\ (\text{BTU/yr})\end{array} = \frac{\text{Annual Output Energy from SP or DH}}{\text{Conversion Efficiency SP or DH}} \qquad (5.20)$$

$$\frac{(\text{kWh/yr})\ (\text{MJ/kWh})}{0.\text{xx}} \text{ or } \frac{(\text{BTU/yr})}{0.\text{xx}}$$

The characteristics of the complete system (gasifier/generator or gasifier/boiler) can be seen by multiplying Equations 5.14, 5.15, and 5.16 for the gasifier by 5.17, 5.18, 5.19 and 5.20 for the shaft-power or direct-heat systems. Gross efficiencies for the whole system will be lower than for the gasifier alone due to the cumulative effect of energy losses. Simply stated, more components in a system increase energy wastage.

The output (usable) energy in Equation 5.19 adjusts the rated energy production (the maximum hourly energy output of the boiler or generator) by the system's actual utilization capacity and amount of downtime or outages. The utilization capacity is the average production load over the maximum load, i.e., the percentage of total capacity actually used on a day-to-day basis. Downtime is the amount of time a system is down for repairs. To avoid miscalculations, an analyst should make sure the utilization capacity does not already include downtime. If utilization includes downtime, then downtime should be dropped from the equation.

The actual fuel demand needed to produce a given level of usable energy can be found using Equation 5.20. The annual input (received) fuel demand is simply the annual usable energy produced by a system divided by the system's conversion efficiency. The following section gives typical efficiencies and energy characteristics for gasifiers.

Gasifier Data

Many factors affect gas production and conversion efficiencies. Some factors are poor design and operating problems, contamination of gases with tars or oils, and underutilization. For these reasons, caution is needed when using average production and energy content figures (e.g., MJ/m^3 or BTU/SCF). Wherever possible, a range of values taken from field units operating over a period of time, preferably a year or more, should be used.

Gasifiers are characterized according to their average energy outputs, along with other gas technologies (Table 5.5). Gasifiers produce two low energy gas (LEG) forms: producer or low-BTU gas and generator gas. Thus, the energy potential of low-BTU gas ranges from 80–200 BTU/SCF (84–210 MJ/m^3). Be aware that these figures assume the systems are well-maintained and have high-capacity use and may overstate field performance.

Energy conversion rates and the hourly amount of produced gas vary widely with different gasifier designs. Gross combustion efficiencies for gasifiers range from 77–85 percent. In the Energy Mission Reports (1982), the gasifier combustion and heat transfer efficiency used for a direct-heat (3MMBTU/hr) hot-air gasifier was 85 percent. This efficiency assumes high utilization rates.

In addition to conversion efficiency, another useful specification for a gasifier system is its turndown ratio. Turndown ratio (R) is the maximum possible gasification rate divided by the minimum possible gasification rate. It compares the maximum potential production with the minimum capabilities of a system. Fixed bed (up- or downdraft) gasifiers typically have high turndown ratios, allowing flexibility in their gas production. This characteristic is an asset if intermittent or varying load (energy) demands exist, as with some engines and heating needs. Fluidized bed gasifiers have a narrower range (R=2), indicating they must run near capacity or will actually have to be stopped and restarted (SERI 1979).

Table 5.5. Energy Content and Uses of Fuel Gases

Gas Type	Source	Energy Range (BTU/SCF)	Use
Low energy gas (LEG)[a] (producer gas, low BTU gas)	Blast furnace, water gas process	80–100	On-site industrial heat and power, process heat.
Low energy gas (LEG)[a] (generator gas)	Air gasification	150–200	Close-coupled to gas/oil boilers; operation of diesel and spark engines; crop drying.
Medium energy gas (MEG) (town gas; syngas).	Oxygen gasification Pyrolysis gasification	300–500	Regional industrial pipelines; synthesis of fuels and ammonia.
Biogas	Anaerobic digestion	600–700	Process heat, pipeline (with scrubbing).
High energy gas (HEG) (natural gas)	Oil/gas wells	1,000	Long-distance pipelines for general heat, power, and city use.
Synthetic natural gas (SNG)	Further processing of MEG and biogas	1,000	Long-distance pipelines for general heat, power, and city use.

Source: Reed (1981, p. 198).

[a] Typical type of gas produced from gasifiers.

Feedstock characteristics are also important to gasifier performance. The gasification properties of various biomass fuels are shown in Table 5.6. The best fuels for the Pacific are wood, coconut shells, and charcoal. As these feedstocks are abundant in the Pacific islands, their use should be promoted over importation or development of nonindigenous biomass fuels. The gasifiers in French Polynesia are currently fueled by coconut shells, whereas wood is used in the Cook Islands and Northern Marianas.

Gasifier Economics

Many problems hinder accurate economic assessment of gasifiers. First, few long-term economic or financial studies exist. Second, the analyses that do exist are usually based on projected costs. These analyses may severely underestimate the set-up and operating costs, two costs that are extremely important to developing countries. When financial or economic assessments are being made, energy analysts should remember that costs supplied by manufacturers are quite tentative and need careful examination.

Annual average and marginal cost analyses are made for nine direct-heat gasifier systems in the Energy Mission Reports (1982). An example of an annual average cost analysis for a gasifier retrofit system in the Cook Islands is outlined below. The gasifier is retrofitted into a laundry direct-heat system of two (100-lb/hr) Anderson boilers. Woodchips are burned in the gasifier, replacing diesel fuel. The costs include the gasifier's capital and O+M costs, whereas the benefits equal the diesel savings, i.e., fuel and O+M diesel system costs. No capital charges exist for the diesel system, given the boiler's age. The energy assessment and financial analysis section are as follows:

Example:

The assumptions for a gasifier retrofit in the Cook Islands are:

- Woodchips are burned in the gasifier at 12,500 MJ/MT
- Gasifier retrofit is 2,844 MJ/hr (3 MMBTU/hr)
- Gasifier gross efficiency is 85 percent
- Gasifier life is 10 years
- Gasifier displaces 21,000 lb/hr steam from diesel boilers

The calculations for the energy assessment are

Annual Diesel Input Energy Displacement = (2,000 liters/mo) (37.8 MJ/liter) (12 mo)

= 0.91×10^6 MJ/yr

Table 5.6. Comparison of Experimental and Calculated Higher Heating Values (HHV) when Gasifying Various Fuels

Material	Experiment HHV (BTU/lb)	Dulong-Berthelot[a] Calc. (BTU/lb)	Dulong-Berthelot[a] Error (%)	Tillman[b] Calc. (BTU/lb)	Tillman[b] Error (%)	IGT[c] Calc. (BTU/lb)	IGT[c] Error (%)
Fresh biomass							
Douglas fir	9,052	8,499	−6.1	9,114	+0.7	9,152	1.1
Douglas fir bark	9,500	9,124	−4.0	9,848	−3.5	9,694	2.1
Pine bark	8,780	8,312	−5.3	9,114	+3.8	8,947	1.9
Western hemlock	8,620	7,840	−10.7	9,757	+1.6	8,536	−1.0
Redwood	9,040	8,441	−6.6	9,340	+3.3	9,115	0.8
Beech	8,906	8,311	−5.1	8,990	+2.6	8,990	0.9
Hickory	8,610	8,036	−7.3	8,620	−0.6	8,746	1.6
Maple	8,671	7,974	−7.1	8,802	+2.6	8,684	0.2
Poplar	8,920	8,311	−6.8	8,990	+0.8	8,990	0.8
Rice hulls	6,610	8,128	−7.3	6,520	−1.4	6,707	1.5
Rice straw	6,540	6,160	−5.8	6,652	+1.7	6,648	1.7
Sawdust pellets	8,814	8,503	−14.9	8,156	−7.8	8,270	−6.2
Animal waste	7,380	7,131	−3.4	7,310	−1.0	7,542	2.2
Municipal solid waste	8,546	8,128	−4.9	8,231	−3.7	8,642	−1.1
Paper	7,572	6,582	−13.1	7,441	−1.7	7,329	−3.2
Absolute average error			7.2		2.5		1.7
Bias error			−7.2		−0.2		+0.4
Chars							
Fir bark	8,260	7,961	−3.6	8,663	+4.9	8,184	−0.9

Rice hulls	6,100	6,026	−1.2	6,050	−0.8	6,058	−0.7
Grass straw	8,300	8,309	+0.1	8,870	+6.7	8,403	1.2
Animal waste	5,450	5,722	+5.9	5,768	+5.8	5,830	7.0
Municipal solid waste	8,020	8,399	+4.7	9,603	+19.7	8,088	0.8
Absolute average error			3.1		7.6		2.1
Bias error			+1.2		7.3		+1.5

Source: SERI (1979).

[a] Dulong-Berthelot Equation: HHV, BTU/lb = $146.76\ C + 621\ H - \frac{N + O - 1}{8} + 39.96\ S$.

[b] Tillman Equation: HHV, BTU/lb = 188 C − 718.

[c] IGT Equation: HHV, BTU/lb = 146.58 C + 568.78 H + 29.45 − 6.58 A − 51.53 (O + N).

Nomenclature: All values are weight percent, dry basis.

A = Ash
C = Carbon
H = Hydrogen
N = Nitrogen
O = Oxygen
S = Sulfur

% Error = 100 (Calc. HHV − Exptl. HHV)/(Exptl. HHV)

$$\text{Absolute Average Error} = \frac{1\%\ \text{Error}}{\overset{n}{N}}$$

$\overset{n}{N}$ = number of data points.

$$
\begin{aligned}
\text{Output Energy} &= (0.91 \times 10^{6}\ \text{MJ})\ (0.90)\ \text{diesel gross efficiency} \\
&= 0.82 \times 10^{6}\ \text{MJ/yr}
\end{aligned}
$$

$$
\begin{array}{l} \text{Wood Input} \\ \text{Energy Needs} \end{array} = \frac{(0.82 \times 10^{6}\ \text{MJ/yr})}{(0.85\ \text{efficiency})} = 0.96 \times 10^{6}\ \text{MJ/yr}
$$

The calculations for the resource assessment are

$$
\begin{aligned}
\begin{array}{l} \text{Annual} \\ \text{Wood Fuel} \\ \text{Requirement} \end{array} &= \frac{(0.96 \times 10^{6}\ \text{MJ/yr})}{(12{,}500\ \text{MJ/MT})} \\
&= 76.8\ \text{MT/yr}
\end{aligned}
$$

Using these delivered (usable) energy values and annual needs, the cost of diesel fuel per unit of delivered energy is more than double the delivered energy cost from a wood gasifier (Table 5.7). These estimates reflect general financial cost analyses from other studies; e.g., gasification compared with diesel fuel usually looks quite attractive financially. It cannot be overemphasized, however, that the constraint on current gasifier use in the Pacific islands and other developing countries is not financial infeasibility; instead, technical, resource supply, and operating problems are the reasons gasifiers still remain pilot projects in most countries. If the resource supply and operating problems can be solved, there is no question that gasifier technology will be preferred over other biomass conversion systems for providing medium-scale electrical and heat needs. Direct-heat systems, which can be used for drying tea, copra, wood, and coffee, are already technically proven and economical (Energy Mission Reports 1982).

SOLAR TECHNOLOGY

Solar energy systems have great potential in the tropics if economically feasible compared with other technologies. In the past, solar technologies have had limited commercial adoption in the Pacific because of high capital costs and high total costs relative to fossil fuel systems. Recent economic and technical improvements significantly reduced solar system costs, so renewed interest in these systems has occurred. More importantly, solar energy systems currently are being produced specifically for tropical environments. These technical adaptations have greatly increased the potential for solar energy systems, particularly photovoltaic systems. Vigorous follow-up studies on the operations and economics of in-field projects are required at this point.

Table 5.7. Annual Average Costs and Benefits from a Gasifier Retrofit in the Cook Islands (1981 New Zealand Dollars)

Costs/Benefits	Annual Average Costs (NZ$/yr)	Delivered Energy Costs[a] (NZ$/MJ Delivered)
Costs		
Capital charge[b]		
Gasifier ($16,500)	2,685	na
Operating and maintenance		
Wood fuel ($25/MT)	1,920	na
Gasifier maintenance (5%)	825	na
Boiler maintenance	392	
Total costs	5,822	0.01
Benefits		
Diesel fuel[c]	14,736	na
Operating and maintenance (3% capex)[d]	392	na
Total benefits	15,128	0.02
Net benefits	9,306	0.01

Source: Energy Mission Reports, Cook Islands, Appendix 4.3.1 (1982).

[a] Delivered energy is 0.82 X 10^6 MJ/yr.

[b] Capital charge i = 10%, 10-year life.

[c] Boilers used 2,000 l/mo at 61.4/liter.

[d] Capex = capital expenditure.

Solar technology can be divided into two distinctly different classes. The first involves solar thermal technology, which converts the sun's energy to heat; an example is a solar water heater. The second class is solar photovoltaics, which directly converts solar energy to electricity; solar lighting and communication installations are such examples.

Solar thermal technology is a mature technology. The designs currently being used for heating water have changed little from the 1880s. The tens of thousands of solar water heaters sold in the United States in the late 1800s and early 1900s are almost identical to models being manufactured today. Likewise, the hundreds of thousands of solar water heaters installed in Israel since the 1950s have changed little in design through the years (Butti and Perlin 1980).

Even the technology to produce high temperatures using parabolic mirrors and other concentration methods are not new. In the mid-1800s, tracking parabolic collectors provided power for small machines. In the early 1900s a field of linear parabolic concentrators powered an irrigation pump in Egypt. Though materials and controls have improved, the systems differ only slightly in basic solar design from earlier models.

In contrast, a major technological development in solar applications came in the 1950s, when the silicon photovoltaic cell was invented. Although methods to convert light into electricity have been known for more than a hundred years, none provided the conversion efficiency or the durability of the silicon cell. In the thirty years since its invention, the solar cell has changed from a laboratory curiosity to a power generator providing many megawatts of electrical capacity on earth and in space.

The energy analyst should be familiar with several commonly used terms related to solar technology. **Collectors** are the parts of the solar unit exposed to the sun; they "collect" the solar energy. **Storage** refers to the part of a solar system that allows energy to be stored for use when the sun is not available. For thermal systems, a tank of heated water may be used for storage; for electrical systems, storage batteries are common. An **inverter** is an electronic device to convert direct current (DC) to alternating current (AC) at high efficiencies. A **selective surface** is a special collector coating that reduces heat loss and improves solar collection efficiency. **Glazing** is the clear cover over a collector that lets solar radiation reach the collection surface but keeps heat from escaping. Glass is the most common glazing material but some plastic is used. Two layers of glazing, called **double glazing**, may be used in cold climates to further reduce heat loss, although some solar energy is lost by passing through both layers.

The **collector tilt angle** is the angle of the collector measured from the horizontal. For most Pacific applications, the optimum tilt is equal to the latitude angle of the site. The **collector azimuth angle** is the direction that a tilted collector points. Some books published in the Northern Hemisphere use south as zero and measure the azimuth angle in degrees to the east or to the west of south. Books published in the Southern Hemisphere may use north as zero and measure azimuth in degrees to the east or west of north. A third group of references uses the compass system, with zero being north and azimuth angle increasing clockwise for 360 degrees. In this last system, east is 90, south 180 and west 270 degrees. For sites in northern latitudes, optimum collector azimuth is due south. For those in southern latitudes, the optimum collector azimuth is due north.

The Sun as a Source of Energy

All of the sun's energy that reaches the earth's surface is in the form of radiation. Only radiative energy can cross the millions of kilometers of empty space between the earth and the sun and pass through the many kilometers of air surrounding the earth. This radiation is composed of about half visible light and half infrared light, which we cannot see but we feel as "heat" radiation. A small component of the sun's energy is radio, x-ray and ultraviolet radiation, but little of it reaches the earth; the amount of energy is small compared with the energy in visible and infrared radiation (Kreith and Kreider 1978).

Users of solar radiation for energy face a primary problem of source unreliability. The sun itself is not at fault. Solar energy applications in space find the extraterrestrial radiation a stable, predictable energy source. Problems caused by solar energy as a variable, unreliable energy source are caused by the atmosphere and the earth's motions in space. Atmospheric changes produce clouds and haze, which result in major, unpredictable changes in solar energy at the earth's surface. These variations influence the design of solar devices. Energy storage systems may be required to average the energy received during a 24-hour period to ensure energy availability at any time. To gain the most energy, the collection device must either point where the sun's motions average out or track the sun across the sky. Systems must be large enough to work when the sky is not clear and when energy levels are lower than optimum. To further complicate solar design, solar radiation is not a concentrated energy source. When the skies are clearest and the sun is most intense, one square meter of the earth's surface barely receives a kilowatt of power, a few cents' worth, in an hour.

Solar Applications

Applications requiring constant, high energy levels are costly because of solar radiation's variable nature and low intensity. The lowest cost applications are those that have intermittent loads (energy demand at any given time), preferably during the day or soon after sunset, and low power levels. In the Pacific, water pumping, water heating, and lighting fit those requirements. Air conditioning and desalination require higher power levels and are limited to areas where the alternative costs are very high or solar availability is exceptionally good. Large-scale electrical power production does not seem practical for the Pacific at this time.

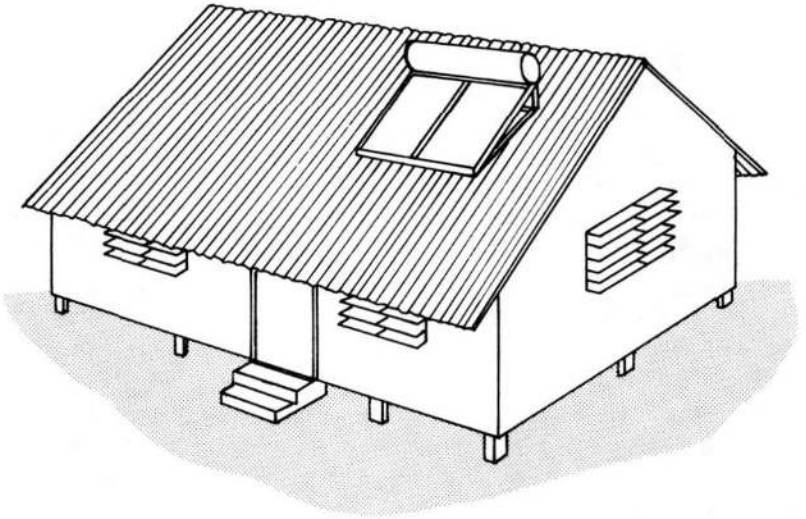

Figure 5.1. Typical household solar water heater.

Water Heating

All solar water heaters include three basic components: collector, storage, and fluid transfer units. The collector converts solar radiation to heat and transfers it to the water (Figure 5.1). The collector surface converts radiative energy to heat by absorbing the light. The efficiency realized in converting radiative energy to heat varies with the operating temperature of the collection surface. The hotter the collector, the lower the efficiency. The most efficient collection will occur when the collector only has to raise the water temperature a few degrees. Then the conversion efficiency may be as high as 85 percent. The least efficient collection occurs when high temperatures are required. The highest temperature that can consistently be obtained with most simple collectors is 60° to 70°C. For domestic water heating, 50° to 60°C is usually hot enough, allowing conversion efficiencies of 20 to 40 percent (Meinel and Meinel 1977, Kreith and Kreider 1978).

In selecting a collector for the Pacific's unusual environment, several construction details should be included.

1. The case and all mounting, bolts, and screws should be stainless steel, aluminum, or heavily galvanized steel.
2. The glazing must be tempered glass or impact-resistant plastic; if plastic, the glazing should not be wrinkled and should be guaranteed against deterioration for at least five years.

3. Pipes carrying water inside the collector should be copper or stainless steel rather than galvanized steel or aluminum.
4. The internal piping arrangement should have many pipes laid parallel and connected together at the top and bottom rather than a single pipe snaking back and forth across the collector.
5. Selective surfaces or double glazing are not necessary in the Pacific except for high-temperature systems; if they cost more, the slight added efficiency is usually not worth the extra cost.

The energy storage unit for water heating is usually an insulated tank with a capacity to provide expected hot water needs during the night. The tank and collector sizes should be matched since too large a tank will not allow a small collector to heat the entire water mass in one day. Too small a tank may cause the water to come to its maximum temperature early in the day. Typically, domestic water heater tanks are between 30 and 70 liters in total capacity for each square meter of collector area. The tanks should be well insulated and must be able to withstand whatever pressure might be applied.

Methods used to transport water between the collector and the storage unit vary with the application. For home-sized systems, self-circulating thermosyphon connections are used. When the storage tank is physically mounted higher than the collector and the collector is mounted with a tilt angle of around 20 degrees or more, the hot water produced in the collector automatically rises to the tank, so no pumps are required. For a thermosyphon system to work well, the tank-to-collector connections should have few sharp bends to keep pipe friction to a minimum and the hot water pipe should be insulated.

Pumps will be necessary to circulate the water at sites requiring tank placement below the collector or more than a few meters away. In pumped systems, a temperature-sensing controller turns the pump on only when the collector is hotter than the water in the storage tank. The added complexity of including a pump and a control significantly increases installation, operation, and maintenance costs and should be avoided for small, home-sized systems. Large hotel- or industrial-sized water heating systems designed for freezing climates usually use a pump to circulate a nonfreezing fluid rather than water through the collector. In the Pacific, freezing is not a problem except in a few high-altitude locations; such elaborate systems rarely are justified economically. Large hotel or industrial systems should be sized by engineers who are experienced in solar system design. But home-sized units are best sized based on the experiences of homeowners already using the systems; local manufacturers, distributors, and installers can also usually provide such advice. Because hot water use patterns differ from culture to culture, a single sizing rule cannot be devised for home-sized solar units.

Large units for commercial establishments suffer fewer installation flaws since their high cost justifies professional design and construction. Operation and maintenance are the primary problems with commercial units. More complex systems require trained operation and maintenance personnel, which are rarely found in the Pacific. Any contract for a large-scale installation should include operator training and an extensive maintenance guide. Since most large solar installations are custom designed, contractors rarely take the time to properly document the installation or provide a complete troubleshooting and operations manual. A contract for solar installation services should always provide for a complete set of manuals specifically for that installation.

Improper installation is the most common problem with solar units. Common errors include installing thermosyphon systems with insufficient height between the top of the collector and the bottom of the tank (the optimum seems to be about one-half meter), failing to insulate hot water pipes or tanks, and using small pipe and many sharp bends for the connecting tank and the collector. Collectors that are improperly aligned with the sun or poorly mounted are not unusual. Satisfaction with home water heating systems depends a great deal on use patterns. Educating the customer in the proper use of the solar unit leads to maximum benefit from the installation.

Photovoltaic Systems

Photovoltaic systems, like water heaters, consist of three basic elements. The photovoltaic panel is the solar collector, a control unit corresponds to the water transport section, and storage may be a storage battery or, in the case of a water pumping unit, a water tank. A few types of photovoltaic systems, such as irrigation pumps, have no control unit or storage but deliver the energy just as it is received from the sun.

The photovoltaic panel consists of a number, often 36, of individual solar cells. Each cell is a small generator capable of producing about one-half volt (direct current) at a few amperes. A photovoltaic panel is created by connecting these cells and mounting them in a sealed case. Panels with virtually any voltage and current capacity can be created by properly interconnecting the individual cells. Currently the most common voltage is 16 to 20 volts and the most common panel size is from 35 to 40 peak watts (Wp) capacity. Panels can be connected for higher voltages or watt capacity.

The control unit is designed to adjust the panel's output to properly meet the requirements of the load connected to the system. Battery charging typically is the load, and the control is supposed to prevent either overcharging or excessive discharge of the battery. A battery storage system must be designed to handle the stress of continual cycling between charge and partical discharge without causing damage. Automobile batteries have a short life in such applications. Special deep discharge batteries specifically designed for photovoltaic service are available; units designed for electric vehicles or wind power applications are also suitable. The cost of these batteries is more than twice as much as that of an auto battery but their life is so much longer that they should always be used.

Presently, solar photovoltaic units provide power for many remote telecommunications systems in the Pacific. Lighthouses and buoys are often powered by solar photovoltaic systems. Other uses becoming more common are home lighting and water pumping in areas without electricity.

Several economic studies of solar photovoltaic systems in the Pacific indicate that photovoltaics are competitive with small diesel plants, particularly in very remote sites where diesel fuel, access, or maintenance is costly (Wade 1983). Unit reliability, when properly installed, has been high and performance satisfactory.

Problems with photovoltaic installations include: (1) attempts to draw more power from the system than it is capable of delivering, resulting in battery damage or customer dissatisfaction; (2) failure of the system's low voltage fluorescent light fixtures because of the use of designs that were intended for intermittent automotive rather than continuous home use; and (3) control system failures caused by customer abuse or designs unsuitable for the tropical climate. The panels rarely fail and, short of physical damage, are unlikely to be damaged by the customer. Panel problems that have occurred are usually related to panel case corrosion or improper sealing, which allows water to enter the panel interior and cell damage to occur. Modern panel construction methods include stainless steel cases or anodized aluminum and silicone rubber encapsulation of the cells to reduce problems.

PHOTOVOLTAIC SOLAR ENERGY EQUATIONS

Although a standard photovoltaic kit for household lighting is probably sufficient for sizing rural lighting systems, several equations are useful to solar photovoltaic energy assessments. As noted in Chapter 4, the amount of actual or estimated daily solar radiation hitting a proposed site must be calculated before an estimate of the solar energy from a photovoltaic system can be made. The following equations apply to the gross efficiency of a solar system, from which can be calculated the delivered or usable energy, system sizing, and average daily load demand.

The gross or overall system efficiency (Eff_{sys}) is a product of the efficiencies of the system's components (e.g., solar cells or module, concentrator, battery, inverter, and charge controller) and end-use technologies (e.g., water pump, heater, lights, or refrigerator). The overall efficiency can be written as:

$$\text{Eff}_{\text{sys}} = \text{Eff}_{\text{module}} \times \text{Eff}_{\text{battery}} \times \text{Eff}_{\text{inverter}} \times \text{Eff}_{\text{end use}} \tag{5.21}$$

where the module efficiency (Eff_{mod}) at a given cell temperature (T) is a ratio of the maximum power produced by the module (set of photovoltaic cells or collector) to the product of the gross area times solar irradiance (Rosenblum 1982). This relationship is:

$$\text{Eff}_{\text{mod}}\,(T) = \frac{(\text{Maximum Power})}{(\text{Panel Area})\ (\text{Solar Irradiance})} \times 100\% \tag{5.22}$$

$$\frac{(W_p)}{(m^2)\ (W/m^2)}$$

The maximum power is the peak power (P_{max}) as expressed in peak watts (W_p). A standard photovoltaic panel may have a 35 or 40 W_p rating. The area for a photovoltaic module is the total area including grid and contacts. For a solar concentrator, the area is the illuminated area on which energy is concentrated. A general relationship between efficiency and temperature is that as temperatures rise, the module or concentrator efficiency falls, producing an inverse relationship. According to Rosenblum (1982), efficiencies for a representative 1980–1982 photovoltaic module with a flat-plate collector would be 9 percent at 28°C (82°F), 8.2 percent at 45°C (113°F), and 7.5 percent at 60°C (140°F).

Battery efficiency is affected by the load demand—energy needs at a given time period—to be met by the battery. Load demand is the actual amount of energy use (kWh) or power (kW) supply needed to meet user needs. As a rule of thumb, batteries are usually assumed to be 20 percent efficient. Other system losses occur in components such as the inverter, wiring, and charge controller. Each of these efficiencies should be included in the overall system's efficiency. Given that efficiencies are multiplied, the overall efficiency of solar systems can be quite small (7–9 percent) compared with other renewable energy technologies.

After calculating the peak watt hours and average daily solar radiation (see Chapter 4), the energy analyst can estimate the necessary size and storage needs for a proposed solar system. Equations for sizing the module array (the set of photovoltaic panels) and battery storage are adapted from Rosenblum (1982) and Richmond (1984).

The equation for module sizing, with module efficiency included in module wattage, is:

$$\text{Modules (Photovoltaic Panels or Collectors) (\#)} = \text{Daily Load of System (kWh/day)} \div \text{Daily \# Peak Sun Hours (hrs/day)} \div \text{Module Peak Wattage } (W_p) \tag{5.23}$$

The module peak wattage assumes module efficiency has been included by the manufacturer in determining peak wattage.

The equation for determining the battery storage requirement if storage days are known is:

$$\text{Battery Storage Requirement (kWh)} = \text{Daily Load of System (kWh/day)} \times \text{Max. Days without Sun (Days)} \div \text{Eff}_{\text{bat}} \text{ (0.xx)} \tag{5.24}$$

The equation to determine the battery requirement is:

$$\text{Batteries Required (\#)} = \text{Battery Storage Requirements (kWh)} \div \text{Rated Battery Capacity (kWh)} \tag{5.25}$$

The equation to calculate the maximum storage days (the maximum days of autonomy) is:

$$\text{Maximum Days of Autonomy} = \frac{\text{Working Capacity of Battery (kWh)}}{\text{Daily Load (kWh/day)}} \tag{5.26}$$

Example:

An energy planner is trying to roughly size a solar lighting kit for a chosen site to check the manufacturer's estimates. The kit consists of three 20-watt fluorescent light bulbs, a battery, a solar panel, and a controller. The users want five hours of lighting per day, the battery is expected to add an additional 20 percent load on the system, the battery's daily depth of discharge is 25 percent, and the battery's efficiency is 80 percent. Given the generally cloudy conditions of the site, the system may have a week without direct sun. To determine the system's days of autonomy, when the system can run off of only stored power in the battery, the following calculations are made:

System Load

Total Daily Lighting Load = (3) (20 W) (5 hr/day) = 300 Wh/day

Additional Battery Load = (0.20) (300 Wh/day) = 60 Wh/day

Total Daily Load = 300 Wh/day + 60 Wh/day = 360 Wh/day

Battery Capacity

$$\text{Working Capacity} = \frac{\text{Daily System Load}}{\text{Depth of Discharge}}$$

$$= \frac{360\ \text{Wh/day}}{0.25\text{/day}} = 1{,}440\ \text{Wh}$$

$$\text{Total Capacity} = \frac{\text{Working Capacity}}{\text{Battery Efficiency}}$$

$$= \frac{1{,}440\ \text{Wh}}{(0.20)}$$

Selecting a battery for a 5-hour discharge rate and a needed total capacity of 1,800 Wh on a battery chart gives a battery with 1,980 Wh/day capacity.

Working Capacity of Selected Battery = (1,980 Wh) (0.80)

= 1,580 Wh

$$\text{Days of Autonomy} = \frac{(1{,}580\ \text{Wh})}{(360\ \text{Wh/day})} = 4.4\ \text{days}$$

Because the site may experience five to seven days without adequate sun; this system's days of autonomy may be a bit low:

SOLAR LIGHTING SYSTEMS

Photovoltaic lighting units for homes have become relatively standard and typically consist of a 35- to 40-watt panel, a battery designed for photovoltaic service with a capacity of 55 to 95 ampere hours, an electronic controller designed to prevent deep discharge of the battery, two 12- to 15-watt high-efficiency fluorescent lights, a plug for operating a radio or cassette player, a night light, and sometimes a nickel-cadmium battery charger for "C" or "D" cells used in portable lights. A system of this type will operate the main house lights from four to six hours a night and the night light all night; it also will provide intermittent power for a radio or cassette player. The system is reliable but provides no excess capacity for any other appliances.

Maintenance is generally less of a problem with photovoltaic units than with any other energy technology, including diesel, since the panels are reliable and the other components are easy to replace at relatively low costs. The primary problem with photovoltaic units in homes is the user's lack of understanding about their limitations. It is still common to find extra lights or even video players hooked into photovoltaic systems, resulting in early battery failure or controller destruction. Clearly, users must be informed that the unit cannot be considered a power source for more than the basic two lights and will fail if loaded beyond this basic capability.

SOLAR WATER PUMPING

Photovoltaics-powered water pumping may be economically competitive with diesel at remote sites, particularly for small systems. Large-scale irrigation systems rarely can be powered by photovoltaics as cheaply as by diesels, however. A typical village water pumping scheme will use panels providing from 200- to 1,000-watts capacity to directly operate a pump and provide no battery storage. The efficiency of such a system requires a special motor/pump combination specifically designed for variable rate operation. The photovoltaic unit provides direct current, therefore a DC motor is usually used; AC can be provided at some efficiency loss by the use of an inverter. The pump is designed to provide good efficiency at a wide range of speeds since the pump's operating speed will vary according to the available sunlight. At this time, there are some standard solar units for pumping water, although special motors and pumps are becoming widely available through solar photovoltaic dealers.

SOLAR AIR CONDITIONING

Air conditioning would seem to be the ideal use for solar energy since the maximum need for cooling occurs close to the time when maximum solar energy is available. Unfortunately, neither photovoltaic nor solar thermal air conditioning schemes are cost effective at this time. Solar thermal systems not only have high initial costs but also high operation and maintenance costs. Photovoltaic systems have lower maintenance costs but much higher initial costs. Air conditioning in general is more technically difficult than water heating, lighting, or pumping and usually requires specific and expensive engineering design for each installation.

SOLAR DESALINATION

Using solar energy to distill water is a well-developed technology. Unfortunately the amount of water that can be provided by solar distillation is relatively small, usually less than 10 liters per square meter per day of bright sunshine. Large and costly solar arrays are necessary to provide enough water for village needs. Simple square-meter solar stills can provide ample water at reasonable cost for a single family's drinking and cooking needs but require constant attention and are not readily available commercially at this time. Reverse osmosis water purification systems are complex but reliable and can be operated from photovoltaic units. Unfortunately, the cost of such installations is high and is not competitive with diesel in the Pacific unless diesel is very costly.

Solar Energy Economics

The economic feasibility of solar energy systems varies widely depending on the system type, delivered energy form (e.g., lighting, hot water, refrigeration), site-specific conditions, and costs of alternative fuels (Wade 1983). The following simple financial net benefit analysis of annual costs is adapted from data in the Energy Mission Reports (Ponape, Appendix 4.4.2, 1982). A new solar system consisting of solar thermal collector panels is proposed for Ponape to provide hot water for residential use. Financial attractiveness of this solar water heating system, however, should not be interpreted as a general statement about solar water heaters or other solar energy systems.

Example:

Some solar system assumptions for a Ponape solar water heater are made.

- 3-m^2 collector panels
- 300-liter cylinder water storage tanks
- Collector efficiency is 45 percent
- Solar collector life is 15 years

- Hot water energy consumption in Kolonia is estimated to be 2,500 kWh per year per household (6.8 kWh/day)
- Diesel is currently used to generate electricity for hot water systems
- Diesel use is 861 liters to produce 2,333 kWh energy in diesel generators, with transmission losses of 12 percent
- Average daily insolation (I_d) is 15 MJ/m^2 · day (estimated from Lae, PNG)
- The minimum mean daily value is 15 MJ/m^2 from May to September, the heavy rainfall period

The calculations for the energy assessment are:

$$\begin{aligned}
\text{Usable Solar Energy} &= (3\ \text{m}^2)\ (15\ \text{MJ/m}^2 \cdot \text{day})\ (365\ \text{days})\ (0.45) \\
&= 7{,}391\ \text{MJ/yr} \\
&= 2{,}053\ \text{kWh/yr} \\
\text{Displaced Diesel Energy} &= \frac{2{,}333\ \text{kWh/yr}}{2.7\ \text{kWh/liter}} \\
&= 861\ \text{liters/yr}
\end{aligned}$$

The usable solar energy, 2,053 kWh per year, may be somewhat optimistic since the system production assumption of 365 days per year does not allow for system outages. However, this effect may be countered by using the minimum mean daily insolation value, 15 MJ/m^2.

Examining solar system costs, annual capital costs make up 75 percent of the system's total annual costs (Table 5.8). The adoption of solar energy systems often requires outside funding because of these high initial capital costs.

When comparing total solar hot water costs with diesel-generated electricity costs per unit of delivered energy, the solar system is about half the cost of diesel-generated electricity (Table 5.8). Thus, solar systems are financially attractive when annual average costs are used. However, as noted, high up-front capital costs for solar systems (as would appear on a cash-flow statement) are a significant deterrent for rural household solar adoption. One method that could avoid the high initial capital costs of solar hot water systems to users would be the establishment of a government program to supply and install solar systems with payment by customers to the government equal to current energy costs of users until the system's total costs are paid off. Alternatively, if such payments are funneled into a cooperative, the revenues from the monthly payments, which are equal to or

Table 5.8. Annual Average Costs and Benefits of Solar Water Heating in Ponape, FSM (1981 US$)

Costs/Benefits	Annual Costs (US$/yr)	Delivered Energy Costs (US$/kWh)
Costs		
Capital		
Capital charge 1 + 10%, 15 years	125	0.06
Operations and maintenance		
3% capex	29	0.02
Total costs	154	0.08
Benefits		
Diesel savings (33.3¢/liter)	287	0.14
Net benefits	133	0.06

Source: Energy Mission Reports, Ponape, modified costs from Appendix 4.4.2 (1982).

Notes: Annual delivered energy is 2,053 kWh. Installed cost for 3-m^2 solar collector system is US$950.

perhaps lower than diesel electricity bills, could be used by the cooperative to cover loans, future repairs, maintenance, and eventually replacement.

Recommendations

Water heaters, home lighting units and small water pumps have been demonstrated to be technically and economically practical in the Pacific. They are available commercially and maintenance support is also generally available. Where no electrical grid exists and extension is costly, the systems are cost-competitive.

Before selecting solar equipment, the user or energy analyst should contact as many suppliers as possible to obtain technical summaries and quotations from each. Price and performance variations among suppliers have been large in the Pacific, and considerable care must be taken to obtain the best cost-benefit ratio with solar equipment. In the Pacific, great emphasis should be placed on simplicity, quality of materials, and availability of qualified service facilities. Most economic and technical failures of solar equipment have been due to improper installation and maintenance rather than to poor equipment. Energy analysts should be familiar with the systems before sending for tender by familiarizing themselves with basic references (Richmond

1984, Meinel and Meinel 1977, Duffie and Beckman 1980, and Kreith and Kreider 1978).

It is important that the users of the equipment be trained in its use. They must know what can be expected in terms of performance and, more important, what cannot be expected. Especially with photovoltaic units, an understanding of the battery capabilities and maintenance is necessary for extended battery life. Home-sized systems can be engineered by dealers or on the basis of existing user experience. Larger systems for commercial or industrial users should be carefully engineered by professionals with solar experience. The design engineers should supervise construction to prevent the possibility of local installers altering the system's design.

HYDRO TECHNOLOGY

Technical components of a hydro power system include the intake system, water transport system, turbine system and the power conversion system. As each of these components has a variety of possible forms, total hydro power systems vary greatly. Selecting the optimum combination for large hydro plants is the job of specialists although energy planners should be aware of available options. For small plants of less than 15 kW the options are more restricted and error costs are smaller. As energy planners are more likely to take part in decision making for these mini- or micro-hydro plants than for large ones, the emphasis of this section is on small, village-scale plants.

Several terms are important for the energy analyst to understand. **Hydro turbine** is the unit that converts the power of moving water to rotational power. Types include Pelton, Turgo, cross flow (also known as Bianki or Michell), Francis, Kaplan, propeller, and bulb turbines (Appendix F). Each type has characteristics that make it the best choice for a particular type of hydro installation. **Head** is the elevation difference that water passes through or falls between the intake and the turbine. Also called **hydraulic head**, it is measured in meters. **Headwater** is the water at the point of the system's intake. **Tailwater** is the water leaving the hydro system.

Gross head is the head determined by the actual difference in height between the levels of the headwater and the tailwater. The term **head losses** refers to losses that make the head appear less than the gross head. Friction in connecting pipes, valves, intake, and exhaust structure all contribute to these losses, which are expressed in meters. Head losses usually depend on the rate of water flow through the system. High flow rates cause greater head losses than do low flow rates. **Net head** is the gross head minus head losses. **Design head** is the head at which a turbine operates most effectively. **Rated head** is the lowest head at which a turbine can provide its full rated capacity; other terms are **net rated head, effective head,** or **critical head.** Three sizes of heads can be distinguished: a **high head** is greater than 100 meters; a **medium head** is from 15 to 100 meters; and a **low head** is less than 15 meters.

Penstock is the pressurized pipe carrying the water from the high point in the system to the turbine. **Headrace** is the channel through which water moves along a nearly level path between the stream intake point and the entrance to the steeply sloping penstock. Also called the **millrace,** the channel may be open or may be an unpressurized, closed conduit. The **surge tank** is an open pipe parallel to the penstock and intended to relieve pressure shocks resulting from rapid changes in turbine water use. Also, it can be a pond or tank at the end of the headrace to provide water storage to eliminate sediment from the water and to provide stored water for sudden increases in turbine water flow. **Tailrace** is the channel through which water moves from the turbine exit to a natural channel; it may be an open channel or an unpressurized closed conduit (Figure 5.2).

Demand is the amount of power needed or desired from the hydro system. **Load** is the power provided by a system. It accounts for efficiency losses. **Water discharge** is the volume of flow per unit of time through the turbine, usually measured in cubic meters per second or liters per second for small hydro plants. A **full gate discharge** is the water discharge when the turbine gates or valves are fully opened. In contrast, the **rated discharge** is the water discharge that provides rated power of the turbine when operated at the rated head. As seen in Figure 5.2, the **intake structure** is a structure placed at the headwater to efficiently allow water into the system while blocking entry of damaging materials such as abrasive sand, debris, and fish.

A **micro-hydro** refers to a hydro system of a small size. The upper limit value for micro-hydro systems is not generally agreed on but a typical value for the largest micro-hydro system would be less than 100 kW capacity. **Mini-hydro** refers to intermediate-sized hydro systems, typically 100 kW to 1,000 kW capacity. Both micro- and mini-hydro systems are used in the Pacific.

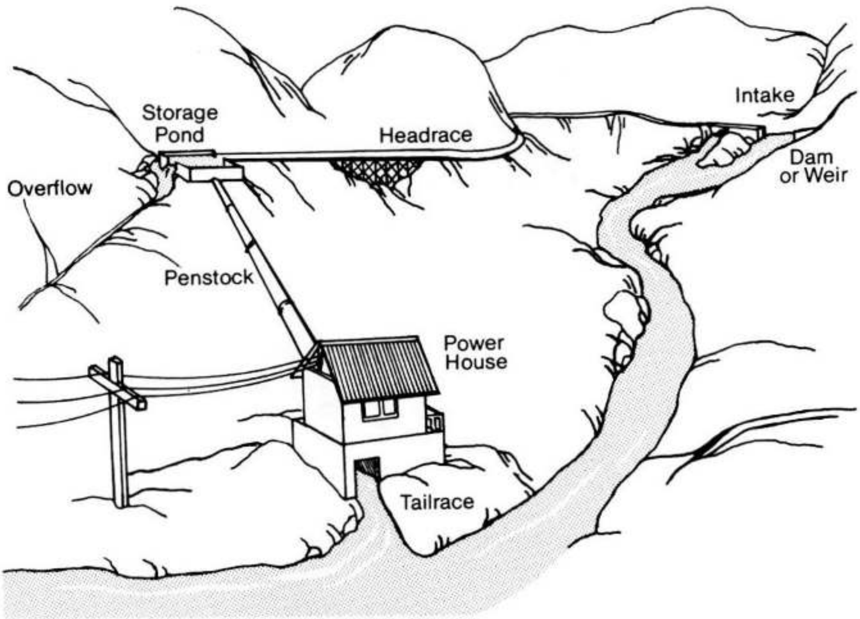

Figure 5.2. Components of a small-scale hydro power system (Source: Adapted from Ashworth 1985).

General Principles and Equations

All hydro plants function by taking energy from moving water. The amount of energy removed depends on the amount of flowing water, the rate of the water flow, and the efficiency of the system. An initial approximation of the power availability may be made using the equation:

$$\underset{(\text{kW})}{\text{Power}} = 9.8 \times \underset{(\text{m}^3/\text{sec})}{\text{Flow}} \times \underset{(\text{m})}{\text{Net Head}} \times \underset{(0.\text{xx})}{\text{System Efficiency}^*} \qquad (5.27)$$

Example:

Assuming a flow of 0.02 m^3/sec (equal to 20 liters per second), a head of 64 meters, and an efficiency of 65 percent, the resulting power is:

$$(9.8)\ (0.02)\ (64)\ (0.65) = 8.15 \text{ kW}$$

Note that the same 8.15 kW would be found with a stream flow half as large but a head twice as high. Likewise, it will take twice the stream flow (or twice the head) to get the same power from a system with half the efficiency.

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* This equation differs somewhat from Equation 4.26 in Chapter 4 by including system efficiency, whereas the system efficiency is incorporated into the constant (6.4) in Equation 4.26.

Since 8 kW is enough to light a village of about 50 households with additional power available for other appliances and a flow of 20 liters per second is typical of the small streams near most Pacific villages, hydro plants for rural villages on mountainous Pacific islands are possible if sufficient head is available close enough to the village to make power transmission practical.

Intake Systems

Two basic types of intake systems are used. **Run of the river** systems use most of the stream flow directly with no attempt to collect a quantity for storage. **Impound systems** include a storage pond or reservoir that helps to average variations in stream flow, acts as a settling basin for solid materials carried by the stream, and provides a relatively deep basin for water collection without the possibility of air entering the hydro unit.

RUN OF THE RIVER SYSTEMS

Run of the river systems generally require minimal civil works. Usually one or more small settling ponds are fed by diverting the stream from its regular bed. Racks or screens prevent larger debris and fish from entering the system; because these methods to remove suspended solids and debris are not very effective, a clean stream or a hydro system insensitive to the presence of abrasive suspended solids or the occasional larger piece of debris is preferred for run of the river systems.

STORAGE PONDS

Impound systems vary from small ponds with only a few hours of storage capacity to large reservoirs with many months or even years of storage capacity. A number of factors influence the size, but for small systems the most common consideration is the need to average the turbine's flow requirements. The amount of water needed to produce power increases directly with the power requirement. For example, with village lighting, low amounts of daily power are needed except in the evening. A storage pond that can collect small stream flows over a 24-hour period and deliver a large flow for a few hours in the evening is preferred to a run of the river installation that is strictly limited to the water flowing in the stream during the evening.

In addition to averaging the turbine's flow requirements, a storage pond also can average the flow of a stream between rains. For streams with small, steep watersheds—typical of mountainous Pacific islands—stream flow rates vary a great deal in a short time. The more variation and the longer the time between cycles, the larger the pond must be.

To calculate the characteristics of a system with a storage pond, it is necessary to know the stream flow characteristics, the load characteristics, and the turbine characteristics. The calculation process is similar to accounting for cash flows through a bank account. The load characteristics determine the turbine's requirement for water at any given time. The difference between the stream flow and the turbine's water requirement to meet the load (all calculated at the same time) is the amount of water that must be available in storage. By adding all these differences during a time period (day, week, month) the storage needs to service the storage pond capacity can be figured.

For small systems where stream flows need to be accumulated to meet high peak demands on a daily basis (as in a system to provide village lighting), the required storage pond volume can be found by assuming a stream flow at or below the observed or estimated minimum and multiplying the flow in cubic meters per second (as determined in Chapter 4) times 3600 (seconds in an hour) times 24 (hours in a day). Then the water demand (the amount of water that must flow through the turbine in a day to meet the load) is calculated using information provided by the turbine manufacturer. If the turbine demand is greater than the daily flow, a daily storage pond will be inadequate. Then either the greatly increased cost of seasonal storage or a reduction of load until daily turbine water demand is less than daily stream flow will be necessary if the project is to be successful. If the daily minimum stream flow is greater than the turbine water demand, a daily storage pond will be adequate. To determine its size, determine the stream flow during the time period the turbine is operating by multiplying stream cubic meters per second times 3600 times the number of hours the turbine is operating. If that flow is greater than the turbine water demand for the day, then a run of the river system with minimal storage is possible. If the turbine daily water demand is greater than the total stream flow during the turbine operating period, then the difference between the two will be the minimum necessary storage. Add at least 15 percent for seepage and evaporation; if the site survey shows that considerable rock, gravel, or silt transport is likely when the stream floods, add 50 percent or more to the pond size and ensure that the users are aware that the transported materials must be removed from the pond periodically. No excess capacity is included in the above; if load increases are expected the storage pond will have to be further increased in size to meet those new loads.

Rarely will a natural storage pond be present at the intake site. A dam is usually necessary to create a storage pond. The large flows that characterize most Pacific streams in flood make earthen and wooden dams difficult to maintain unless the dam is large and includes a concrete or metal spillway large enough to pass the total stream flow during full flood. Reinforced concrete dams of 3 to 4 meters in height can be built with hand labor and the materials can be transported by domestic animals. The dam site should be examined by a geologist to aid in designing the dam's foundation. Since considerable force will be exerted on the dam (tending both to slide it downstream and to turn it over), attachment of the dam to underlying rock is recommended. A number of such dams have been built for water supply purposes throughout the Pacific, and the designs are well established.

Choosing the appropriate turbine for a hydro system depends on the system size, head size, power needs, desired ruggedness of the system (tolerance of foreign matter), and system efficiency. Appendix F describes such turbines as the Pelton, Turgo, cross flow, Francis, propeller, Kaplan, and bulb installation turbines. Engineers should always be consulted in choosing and installing the proper turbine for a hydro system. However, to select the optimum turbine, information on power needs, site characteristics, expected maintenance capabilities, and stream flow must be known. As generally is the case in all energy systems including hydro located in remote areas, the principle of simplicity and low maintenance always holds.

Electrical Generation

Direct current (DC) is rarely generated with hydro power because of problems in distributing the power. Despite their advantages, alternators for producing alternating current (AC) require much closer speed control than DC generators, and voltage control circuitry for AC systems is generally more complicated.

Two types of alternators—induction alternators and synchronous alternators—are currently used with small hydro units. Induction units are only used when the hydro system is connected to an existing power grid because the units require grid power for operation. Less efficient than synchronous alternators, the induction machine automatically matches the power flowing in the grid while synchronous machines require complex switches and control equipment to match the power. Also, the induction alternator connected to the grid does not require complex speed controllers and automatically provides the maximum power then available from the hydro resource. Small low-head turbines, particularly bulb and propeller types, are often grid-connected with induction alternators to eliminate the high cost of speed control devices.

Both brush type and brushless (permanent magnet) synchronous alternators are available. The brush type, mechanically simple, has been used for nearly a hundred years. It is very reliable if the brushes are replaced periodically. If allowed to run until the brushes fail, the rings contacted by the brushes can be damaged, causing major repairs. With the brushless alternator, theoretically the equipment requires no maintenance, except for the bearings, which have a long life. Diode failures occur, however, particularly in hot, wet climates, and diodes are more difficult and expensive to replace than brushes. If the site can be operated with regular preventive maintenance, the brush type alternator is recommended. If maintenance is only likely to be performed when a failure occurs, the brushless system is recommended.

The alternator's rotational speed determines the frequency of its output. Rotational speed must be reasonably constant at the alternator's design speed for it to provide quality power. Large installations are designed to maintain an average speed closer than .001 percent to the design value. As long as loading is constant, rotational speed will also be constant. The problem of speed control arises with varying loads.

The speed control quality required in a micro-hyrdo installation depends on the alternator's characteristics and the load requirements. High-quality alternators with good voltage regulators can maintain constant voltage with poor speed control. These alternators should always be used with micro-hydro systems that are not grid connected. If a hydro generator is set to run properly at a particular load, a smaller load will tend to cause it to overspeed while a larger load will tend to slow it down. To overcome these tendencies, either a constant load is drawn from the plant or some sort of speed control is included. Frequency of equipment run off the hydro power system will always change with speed, however, and appliances containing motors or transformers may be affected by deviations from their design frequency. In general, a speed control that keeps the system within 10 percent of the design value is adequate for a micro-hydro system feeding ordinary domestic loads. Industrial loads that have frequency-critical control systems require 1 percent or higher speed regulation. Large hydro systems often maintain speed control better than .001 percent per day.

TURBINE SPEED CONTROL

Basic speed control in small hydro sets is usually managed with a flywheel. This energy storage device averages out small, short-term load variations, helps prevent the transmission of sudden electrical load changes to the turbine, and allows slow speed controllers to function adequately. The flywheel is often placed on the alternator shaft since it is the source of load change and is usually the highest-speed unit in the system. Load variations exceeding one minute cannot be controlled by even relatively large flywheel systems, and other methods must be employed.

Manual control is the simplest. An operator watches a meter that indicates speed and adjusts turbine speed. While a manually controlled hydro plant is possible, the speed control quality is poor compared with an automatic unit, and the cost of having an operator continually on duty is excessive for a micro-hydro system.

With units of 10 kW and less, systems that present a constant load to the alternator are the lowest in cost and are common. One approach uses the user load to compensate. All lights and appliances are permanently wired into the system; turning a unit off automatically inserts a compensating load into the system. The system is satisfactory for lighting needs but is difficult to wire for appliances with automatic controls such as refrigerators.

Automatic load controllers detect the rotational speed of the alternator by monitoring the frequency of the output current, then add or subtract a load, usually a water or air heater, to keep the system operating at a constant speed. The quality of speed control from such units is excellent, although the systems are electronic and tropical conditions lower their reliability. If such units are installed, spare circuit modules should be kept at the alternator site.

Mechanical speed controls are available but are more expensive than electronic load controllers. Purely mechanical and hydraulic controls both are used with micro-hydro systems. Larger hydro units use hydraulics exclusively. The speed control quality varies from fair to excellent but all, when properly adjusted, will do an adequate job.

If regular maintenance occurs, mechanical speed controllers seem more reliable than electronic units. If maintenance is carried out only when a failure occurs, the electronic systems are more easily repaired because they are external to the turbine/generator unit and have a "plug-in" feature.

Water Transport between the Intake and the Turbine

Water must be moved from the intake site to the turbine in a way that provides a maximum net head for the turbine's design flow. A pipe is required for the water that falls from the headwater elevation to the turbine elevation and provides a head, since the water is under pressure. The pressure pipe, called the penstock, may run from the intake structure directly to the turbine or it may collect water from a channel or nonpressurized conduit that carries the water from the intake structure some distance along the headwater contour.

Since a pressurized pipe is more expensive than an open channel or a nonpressurized conduit, common design practice channels the water away from the stream (but with little height change from the intake structure) as far as possible before the steeply sloped penstock begins. The penstock system is also built away from flood and washout areas. The low slope pre-penstock transport system is called the headrace or millrace. A small pond with its own intake structure is built at the juncture of the penstock and headrace. This ensures that the penstock intake is always under water and removes any leaves, branches, or other debris that may have fallen into the headrace.

Powerhouse

The primary consideration in selecting the powerhouse site is to be certain that the location is above the maximum flood level of the adjacent stream. The powerhouse structure can be any type of enclosure, although it should be secured to prevent unauthorized entry since dangerous electrical and mechanical equipment is operating inside. Large micro-hydro and mini-hydro plants may include air-conditioned areas for controls and switchgear. Impulse-type medium- and high-head turbines may vibrate if not secured to a sturdy concrete foundation. The alternator should be on the same foundation to ensure continuing alignment with the turbine. Controls and valves should be accessible to the operator. Floor drains are necessary since water leaks are a constant occurrence in hydro plants. In all sizes of systems, a communications network between the powerhouse and the load site is useful.

Tailrace

After water leaves the turbine, it flows into the tailrace. Commonly, the water flows back into the stream after flowing through the tailrace.

In a few cases, the powerhouse is not located near the stream and tailrace water creates a new stream. Since the new stream flow is nearly constant, a channel may be dug as an extension of the tailrace to route the water to a natural stream with little fear of massive flood erosion. If erosion is a problem, however, the tailrace extension should be lined with concrete, metal, wood, rock, or other noneroding material.

Economic Considerations

Although a great deal of attention is often given to the cost of turbines and generators for use in a hydro plant, the cost of these items is usually low compared with costs of the civil works (access roads, bridges, buildings) and the power distribution system of the project. Turbine and generator equipment may be purchased in the US$1,000 per kW capacity range but the cost of a typical micro-hydro project is from US$3,000 to more than US$5,000 per installed kW. Costs are reduced by careful planning and management of the civil works component and proper design of the power transmission system rather than by shopping for the cheapest possible turbo-generator unit. Because of the high cost of civil works, each site should be examined for other uses of the dam and impoundment and possibly the water leaving the turbine; these other uses include irrigation, village water supplies, and flood control.

The actual economics of the project can be evaluated only on the basis of cash-flow (life-cycle) costing methods. The economic life of a properly designed hydro project is typically 50 years or more. The primary benefits provided by hydro systems are fuel savings, a high level of reliability, and low maintenance costs. The high capital costs offset these benefits. Both benefits and costs vary greatly from site to site. For micro-hydro systems, benefits are usually greater for stand-alone plants than for grid-connected systems since the costs of diesel-generated power in a remote location are generally much higher than grid-power costs.

In any capital-intensive project, the more the system is used, the better the overall economic situation. The daily use of a hydro plant for five hours to provide village lighting is less economical than providing 24-hour power to an industrial facility. With a diesel plant, operating costs increase rapidly with increased use because fuel costs are a significant proportion of total costs; with a hydro system operating costs increase slowly, if at all. In fact, a hydro plant operated continuously under design load is expected to require less maintenance than a plant operated only four hours a day; operator damage is less likely to occur in continuous operation because of fewer start-stop cycles and constant heat of the electrical equipment, which keeps it dry.

The following example of hydro power economics uses the Lehmasi River development project in Ponape, Federated States of Micronesia (Energy Mission Reports 1982). The Lehmasi River, the largest in Ponape, has high potential for hydroelectric power, but dam construction involves the costs of building roads, power lines, and bridges, too. Road and dam maintenance also could be costly for start-up and operation. If erosion is a problem, dredging costs must also be considered. Although such costs are not included in the financial analysis of dam costs (Table 5.9), they should be included in full economic analysis of the dam.

Unfortunately, the infrastructure and environmental costs were not included in the Energy Mission Reports (1982). A limited economic and a financial analysis is made below by including the full costs of electricity production (social costs) for the government in the economic analysis versus subsidized electricity prices in the financial analysis.

The assumptions and energy capabilities of the dam scheme are outlined below.

Example:

The assumptions for a hydro power scheme for the Lehmasi River in Ponape are:

- Plant capacity is 1.4 MW
- Annual generation is 5.5 GWh
- Average capacity load factor is 45 percent
- Dam life is 40 years
- Interest rate (required return) is 10 percent

In the assumptions, the annual generating capacity (5.5 GWh) considers the 45 percent plant factor and gross efficiency of electricity production (10–15 percent). In Table 5.9, for the financial analysis, benefits equal displaced revenues from diesel generation at the government-subsidized rate. In contrast, the full costs of electricity production are used in the economic analysis. In the financial analysis, capital costs are more than 80 percent of total costs, showing capital's importance to the project. In the financial analysis when the subsidized price and thus current revenues are used as net benefits, the hydro electric scheme loses 13¢/kWh generated. However, if the

Table 5.9. A Financial and Economic Analysis of Annual Hydropower Costs for the Lehmasi River, Ponape, FSM (1981 US$)

Costs/Benefits	Annual Costs (US$000/yr)	Delivered Energy Costs (US$/kWh)[a]
FINANCIAL ANALYSIS		
Costs		
Capital costs[b]		
Capital charge	950	0.17
Operations and maintenance		
Operations/maintenance[c]	186	0.03
Insurance	56	0.01
Total costs	1,192	0.21
Benefits (subsidized)[d]		
Electricity (8¢/kWh)	440	0.08
Net benefits (financial)	-752	-0.13
Break-even selling price	1,192	0.21
ECONOMIC ANALYSIS		
Benefits (nonsubsidized)		
Electricity (23.5¢/kWh)	1,293	0.24
Net benefits (economic)	101	0.02

Source: Adapted from Energy Mission Reports, Ponape, Appendix 4.1.1 (1982).

[a] Delivered energy is 5.5 GWh annually, using a 45 percent plant factor and 1.4 MW installed capacity.

[b] Capital cost for dam plus interest (during construction) is US$9.3 million. Capital charge uses a 10 percent interest rate and a 40-year life.

[c] O+M costs are 2 percent of capital expenditure costs (capex = US$9,300,000). This O+M factor is higher than the 0.5 percent capex used in the Energy Mission Reports, Ponape, as the latter appears to be too optimistic for Ponape.

[d] Subsidized electricity costs in Ponape are 8¢/kWh; actual costs of production (social costs) are 23.5¢/kWh.

real costs of production to the electricity authority for running the current diesel system are used in the economic analysis, the hydro electric plant shows a net gain of 2¢/kWh. Depending on the future political status of FSM, if a shadow exchange rate (perhaps 1.2) for imported capital were used, capital charges would increase to US$1,140,000 per annum or 21¢/kWh.

Therefore, given a 2¢/kWh spread and recalling that infrastructure costs and foreign exchange shadow values are not included in the economic analysis, the hydroelectric dam appears at best marginally attractive. Only if the full social costs of electricity production (21–24¢/kWh) are actually charged would it appear economical; but raising tariffs to recover costs will encourage conservation and dampen incentives for projected expansion. The Ponape example shows the critical paradoxes in economic versus financial analyses and the possible repercussions of internalizing the social costs of proposed energy projects.

WIND TECHNOLOGY SYSTEMS

Wind energy systems are not a new technology. In fact, wind energy has been an important water pumping and grain milling energy source for more than 500 years. Yet, wind energy is often spoken of as a "new and untried technology." What is new and untried are the machines presently being manufactured since few manufacturers have been in operation more than a decade. In the Pacific, few wind machines have been installed and very few of those have remained functional for more than a short time. While satisfactory wind sites certainly exist in the Pacific, the experience level is so low as to make any installation an experiment and should be treated as such.

Potential users should be aware of some commonly used terms. **Mass of air,** although not technically correct in this use, refers to a "unit" mass of air that weighs one "weight unit"; i.e., a pound in the British system or a kilogram in the International System of Units. **Air density** is the mass of air contained in a particular volume of air. The measurement may be pounds per cubic foot or kilograms per cubic meter. The standard density of air is 0.096 lbs/ft^3 or 1.2 kg/m^3. The density changes according to altitude; density decreases—the air becomes thinner—as altitude increases. Also the density decreases as the temperature rises.

Kinetic energy is the energy of motion of a material. It is defined by the equation:

$$E = \tfrac{1}{2}(mV^2), = \tfrac{1}{2}(\text{kg})(\text{m/sec})^2 = \text{J} = \text{kWh} \qquad (5.28)$$

where

E = energy (J or kWh)

m = the mass of air (kg) passing the machine in a unit of time

V = the velocity of air measured as the distance the mass of air travels in a unit of time (m/sec)

The relationship means that if a 1 m/sec velocity is doubled, the kinetic energy (E_k) increases by a factor of 2^2, or 4. If the velocity increases by a factor of 4, then the E_k increases 4^2, or 16 times.

Power, as contrasted with kinetic energy, is defined (Merrill and Gage 1978) as:

$$P = \frac{\text{Change in } E_k}{\text{Change in time}} = \tfrac{1}{2}(\dot{m}V^2)$$

since $\dot{m} = \rho AV$

where ρ = the density of air, then

$$P = \tfrac{1}{2}(\rho AV^3) = \tfrac{1}{2}(\text{kg/sec})(\text{m/sec})^3 = \text{J/sec} = \text{kW} \qquad (5.29)$$

Thus, power increases by the cube of the velocity; for example, if velocity is doubled, then power increases by a factor of 2^3 or 8. These differences between kinetic energy and power are important to bear in mind. Table 5.10 shows the correct units to use for power, velocity, and area.

Swept area is the area covered by the rotation of the blades or equivalent parts of a wind machine. For a propeller-type machine, the mathematical relationship is:

$$A = (3.142)(D^2/4) \qquad (5.30)$$

where

A = the swept area of blades

D = the diameter of the propeller circle

Thus doubling the diameter of the propeller causes an increase in swept area of 2^2 or 4.

Solidity is the ratio of the blade area to the swept area. A solidity of 0.1 indicates that 10 percent of the swept area is blades. An American farm windmill for pumping water has a high solidity of about 0.65. A two-bladed wind electric generator may have a solidity of less than 0.1. High solidity machines usually exhibit high starting torques and good low-wind performance but poor high-wind performance. Low solidity machines are usually much more efficient at medium and high wind conditions.

An **inverter** is an electronic device that converts direct current (DC) to alternating current (AC). The usual use is to change battery power to regular, power-line type AC. A **synchronous inverter** is an electronic unit that takes direct current, usually from a battery, and converts it to power-line quality AC that can be directly fed into and synchronized with an existing power grid that has been energized from

Table 5.10. Appropriate Power, Area, and Velocity Units and Constant Coefficients for Calculating Power Output from Wind Machines

Unit of Power (P)	Unit of Area (A)	Unit of Velocity (V)	Value of K (K)
Kilowatts	Square feet	Miles per hour	0.0000053
Kilowatts	Square feet	Knots	0.0000081
Horsepower	Square feet	Miles per hour	0.0000071
Watts	Square feet	Feet per second	0.00168
Kilowatts	Square meters	Meters per second	0.00064
Kilowatts	Square meters	Kilometers per hour	0.0000137

Source: Merrill and Gage (1978).

Note: Where P = power, A = area of wind machine blades, V = velocity of wind, K = constant including air density and other conversion factors, used in the equation $P = (K)\ (A)\ (V^3)\ (0.5926)$.

another generator. Such a unit allows a DC wind machine to add its power to an existing power grid. A **horizontal axis wind machine** is a machine with a horizontal axis of rotation. This is the most common type and uses propeller-type blades. A **downwind horizontal axis wind machine** is a horizontal axis wind machine with the propeller turning downwind from the support tower. A **vertical axis wind machine** is a machine with a vertical axis of rotation. Several versions exist.

Availability refers to the fraction of time that a wind generator functions. Availability of 0.9 indicates that the machine is functioning 90 percent of the time. In the Pacific, experience places availability well below 0.5 for electrical power generating wind machines (Twiddell and Weir 1985). For water pumping windmills, availability has been much higher, although most machines were ultimately destroyed by exceptionally high winds. The **performance coefficient** is the fraction of total available wind power extracted by a wind machine. The maximum possible performance coefficient for open turbine wind systems is about 0.59. Commercially available wind machines typically have performance coefficients from 0.2 to 0.4. The performance coefficient is the highest at the machine's design wind speed and declines at higher and lower wind speeds.

Rated wind speed is the wind speed at which the rated electrical output is reached. Manufacturers differ greatly in their designs for rated wind speed. Although a detailed analysis of wind speed is necessary to accurately determine the optimum rated wind speed for a particular site, a rated wind speed of 1.5 to 2.0 times the average site wind speed usually results in the installation of a machine that can take advantage of the higher powers of above average winds while also functioning at lower speeds. Manufacturers assign their machines a power rating based on rated wind speed. A 10 kW machine with a rated wind speed of 13 meters per second (m/sec) will have a lower purchase cost than a 10 kW machine with a rated wind speed of 8 m/sec because the former has a smaller blade system (although the generator is the same size). The 8 m/sec machine is preferred, however, if the average wind speed at the site is 6 m/sec because the machine with the higher rated wind speed will operate inefficiently (if at all) at the lower speeds found at the site.

The **plant capacity factor** is the kilowatt-hours of energy delivered by the wind plant over a specified time period (usually a year) divided by the kilowatt-hours that would have been delivered if the plant had operated at full rated output for the entire time period. With most power plants, a high capacity factor is a desirable characteristic. With wind plants, a high plant capacity factor indicates a plant that has a small generator relative to the size of the rotor for the wind conditions that exist (i.e., the rated wind speed is too low). Since the generator is the inexpensive part of the wind plant, this implies that the plant is much more expensive than is warranted. At present costs of wind machines, the economically optimum plant capacity factor seems to be around 0.3.

Wind as a Source of Power

In order to tap the power of wind, the flow of air must be intercepted. The amount of power that can be taken from the wind is determined by the speed of the air flow, the density of the air, and the size of the unit that is placed in the air flow since the available wind power increases by the *cube* of wind speed. If the wind speed triples, the available power increases by a factor of 3^3 (27). This means that there is 27 times as much power in an 18 mph wind than in a 6 mph wind. The power that a wind machine can remove from the air increases directly as the swept area of the machine increases.

Like other energy conversion systems, the actual power delivered by a wind system is lower than the fuel's potential power because of conversion losses. Such losses or inefficiencies are particularly significant with wind machines. Wind machines have a theoretical maximum power output due to simple momentum and energy laws. Also, inefficiencies in the machine's components (alternator, generator, and inverter) add to the overall system inefficiencies.

According to momentum theory, any wind machine has a theoretical maximum efficiency of approximately 59 percent (Eldridge 1980, Merrill and Gage 1978). Even the best system design loses more than 40 percent of its incoming power. In reality, the best commercial systems, such as two-blade motors with high blade tip to free-flow wind speed ratios, have 47 percent power coefficients and most machines fall into the 5 to 35 percent range (Eldridge 1980).

Actual calculation of the overall power coefficient (C_{op}) for any wind machine at a particular wind speed (V) is the ratio of the power generated (or power to load) over the power in the wind (Eldridge 1980). This relationship is written:

$$C_{op}(V) = \frac{\text{Power to Load}}{\text{Power in Wind}} \tag{5.31}$$

$$= \frac{\text{Power Output}}{\text{Power Input}}$$

$$= \frac{\text{Power to Load}}{(\tfrac{1}{2}\rho A V^3)}$$

where

V = wind velocity (m/sec)

A = cross-sectional area of rotor or blades (m^2)

ρ = density of air

The actual delivered power to energy users is also affected by a machine's outage time. After monitoring wind machines for a year in the United States, engineers observed system outages ranging from 21 to 33 percent (Twiddell and Weir 1985). Under tropical conditions, these systems may have even higher outages. By incorporating this outage factor into energy calculations, the expected power output decreases. For instance, a machine with an outage rate of 27 percent and a power coefficient of 35 percent located in an area with potential wind power of 20 megawatt-hours could actually deliver only 5.1 MWh [5.1 = (20 MWh) (0.73) (0.35)].

Machine wind speed constraints also affect a machine's appropriateness for an area. Every machine has a maximum power generation capability, or its rated power. The wind speed that produces this rated power is the rated speed, V_r. This rated speed represents the speed at which the rated power of the generator is possible. Wind speeds above V_r are still converted into power but at lower efficiency. The system, however, will shut down at the furling or cut-out speed (V_f) beyond which it is unsafe for the system to run. The furling speed (V_f)

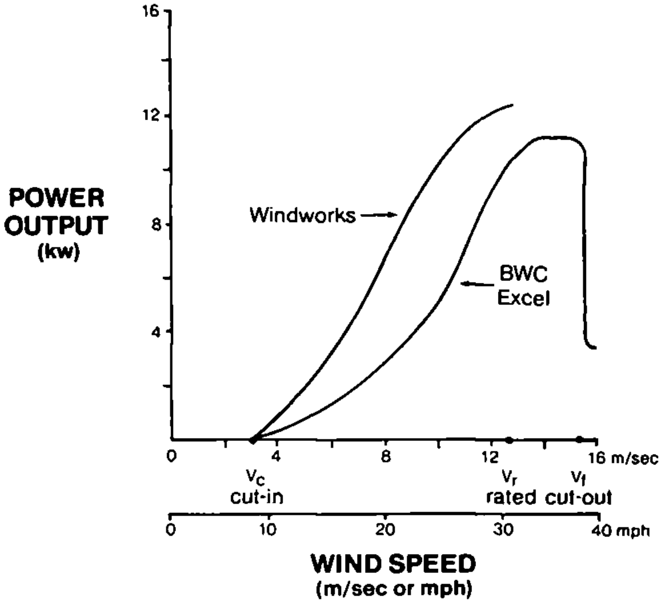

Figure 5.3. Power output and wind speed curves for two proposed wind machines (Source: SPEC 1983).

represents the maximum wind speed at which the machine will run. Besides this maximum upper limit, there is a bottom or cut-in speed (V_c) at which the machine begins generating power. The V_c, V_r, and V_f are shown in Figure 5.3. Power (P_w) is actually generated in the wind speed range V_c to V_f. The annual energy (E_A) that can be produced by any given wind machine is the sum of the time duration throughout the year (D_y) in percentage that wind speeds of V_c to V_f are experienced (Eldridge 1980).

$$E_A = \frac{V_r}{V_c} (C_{op}) (P_w) (D_y) + \frac{V_f}{V_r} (C_{op}) (P_w) (D_y) \tag{5.32}$$

If adjusted for power outages, where PO equals 100 percent minus percentage outage, then

$$E'_A = \frac{V_r}{V_c} (C_{op}) (P_w) (D_y) (PO) + \frac{V_f}{V_r} (C_{op}) (P_w) (D_y) (PO) \tag{5.33}$$

In conclusion, determining the energy output of a particular wind system for a site depends on the machine's design characteristics, the system's commercial reliability and adaptability as it affects outages, and the energy needs of the users.

Site Selection

A large increase in energy (doubled) or power (cubed) for just a moderate increase in wind speed clarifies the importance of the presence of higher wind speeds at a site. The size, and therefore expense, of a wind machine will be directly determined by the amount of available wind; and a site that has 8 mph wind instead of 16 will require a machine that has *eight times* the swept area to give the same power. In terms of a horizontal axis machine, that means a propeller diameter almost three times as big is required (but not eight times as big since the swept area increases as the square of the diameter).

Because the power output is so sensitive to changes in wind speed, the wind machine must be placed where it can use the greatest amount of wind possible—usually high up. Because of the velocity gradient, placing the machine in a high position increases the speed of the wind caught by the machine, at least up to the point where the free wind speed is reached. In particular, the machine will use much higher winds if placed higher than surrounding trees. The coconut trees and dense rain forests on Pacific islands make it particularly difficult to place a wind machine in the best wind position. An expensive tower is required, creating construction problems and requiring quick dismantling during hurricanes. A machine has to be above the tops of the trees 15 or more meters to approach maximum wind speeds and to be clear of the damaging turbulence close to the trees. Turbulence created from buildings or other ground obstructions stresses the machine and the tower and reduces the power conversion efficiency. Many total failures of small wind machines have resulted from turbulence, which literally broke the blades or destroyed the tower.

Safety is another factor in site selection. Should the tower fall over or a blade be lost from the rotor, no damage to property or harm to people should be likely. Electrical components should be inaccessible to all but authorized persons, and warning signs should be clearly displayed. Possible harm to humans or property (such as might occur if the tower fell or a blade broke from the rotor) should be considered in choosing the site.

The importance of proper siting cannot be overemphasized. Since a small increase in wind speed results in a much larger increase in power output, site changes involving just a few meters can significantly change the economics per unit of a site's useful energy.

Choosing a Wind Machine

Wind machine manufacturers are known for providing estimates of machine performance considerably in excess of that found in the field.

In particular, maintenance cost estimates seem far too low for Pacific island conditions. If possible, the potential user should study the results of tests performed by a government agency (Australia, France, the United States, and Denmark have all done extensive wind machine tests) since they appear to be more relevant to actual field performance.

In purchasing a wind machine for a remote site, choose simplicity over efficiency. Simple machines have lower maintenance costs, which can be very high at remote sites. Studies show that few small wind machine manufacturers can provide replacement parts after more than a few years, since most go out of business. Therefore parts probably will have to be custom built, and simple parts made from common materials are easier and cheaper to fabricate.

It is usually best to pay a higher price—even double—for a rugged, high-quality machine from a manufacturer with a good, long-term business record and a clear commitment to the future than to purchase any machine, no matter how financially attractive, from a company that has a limited business history and sells equipment "using the latest technological advances." Maintenance problems are by far the major cause of wind machine project failures in the Pacific and probably everywhere else. If a high-quality, low-maintenance wind machine is too expensive, then alternative energy sources such as hydro or biomass should be considered.

To date, the majority of kilowatts produced by wind machines have been from units with rated power ranging from 50 to 150 kW. Nearly all have been grid connected; i.e., they are not stand-alone systems. None would be economically useful if government subsidies were not involved. Stand-alone systems are less economical if compared with grid-power costs, except for remote sites with good conditions, where they may compete favorably with small diesel generators.

If grid connection is being considered, there are two types of generators available for small systems: (1) a direct current generator coupled to an electronic synchronous inverter, and (2) an induction generator connected directly to the grid. The induction unit is far cheaper and much more reliable than the DC grid-connected system, which should only be considered if the unit must stand alone a significant part of the time. If such is the case, the DC system can charge batteries to feed the synchronous inverter and thereby provide stable AC power at the plant.

Remote installations may use either DC generators or alternators. If an alternator is used, the resulting AC is converted to DC for charging batteries. From the batteries, the DC may be used directly or converted to stable AC with an electronic or mechanical converter. If the wind machine is only to be used to provide heat or to pump water, an alternator may sometimes directly feed the load, since the load can be always matched with the available power and the frequency of the generated power is not important.

Batteries must be designed for heavy-duty, deep-discharge use. Automobile batteries will not survive long although their initial price is attractive. For long, trouble-free operation, even top quality lead-acid batteries specifically designed for wind machine use should be protected against continual cycling between full charge and deep discharge. Battery maintenance is important for long life; water levels must be maintained, and distilled or deionized water must be used.

No wind electric machines that have been specifically designed for tropical climates are commercially available. Pacific island environments with high humidity, salty air, and high temperatures are particularly hard on steel or aluminum structures and on electrical components. Electrical switch gear and electronic controls should be installed in a dry area, preferably sealed from dust and moisture. Hot surfaces should be located where air can circulate freely; small cooling fans may be worth the power loss for cooling particularly hot, critical components. Although more costly initially, electronic equipment with substantially higher capacity than that required may be the best long-term investment because of lower maintenance needs.

A safe procedure to stop the blade rotation must be available during erection and maintenance periods. The process should be capable of ground operation. Tower design is also important. Both guyed and freestanding towers are commonly used. In areas with regular hurricanes, the system should be specifically designed to survive 200 kph winds; small systems should be able to be dismantled in a few hours. Folding and pivoted towers are common and not only allow quick dismantling in the face of a hurricane but also ease of erection and maintenance. Remember, however that by the time a hurricane's passage is known, wind speeds may already be high, therefore the lowering mechanism must work under windy as well as calm conditions.

Selection of the appropriate wind system for a particular site is not a trivial matter. Before decisions are made, advice should be sought from manufacturers, scientific and engineering advisory staffs of international agencies, and technical assistance staffs. Reviewing basic references such as Eldridge (1980), Putnam (1982), and Golding (1980) are important first steps for an energy planner. The cost of failure can be high—not only the direct installation cost but also hidden costs of government project support and removing the system to replace it with something else. The loss of confidence in alternate energy systems in general may be attributed to losses incurred from poorly planned or poorly executed wind projects.

Wind-Power Economics

The availability of good wind conditions does not mean that a wind machine is a reasonable option for power generation. The distance from the site to the users greatly affects the site economics because of power transmission costs.

The available alternatives also make a difference. If grid power produced from hydro generators is nearby, it is a better choice than the installation of a wind machine. Wind machines may be practical if the site is very remote, the load is nearby, the cost of fuel is high, and the power required cannot be met more effectively by photovoltaics or a micro-hydro system.

In analyzing wind power economics, planners should always include an adequate allowance for maintenance. Wind machine maintenance at remote sites has consistently been two to three times higher than estimates provided by machine manufacturers based on their tests or on users' experiences in developed countries. If the unit is to operate as a money-making economic unit, sufficient alternative fuel costs should be included to make up for lost production while the system is inoperative due to maintenance needs. Even with wind machines operated by power companies in developed countries, down time has been a significant cost factor.

Example:

The following wind machine costs come from a proposed wind-diesel supplemented system for Aitutaki in the Cook Islands (SPEC 1983). The machine is to displace only 3 percent of the current annual electric generation from a diesel system. Outside support for capital costs will reduce actual costs borne by the Cook Islands. The system is seen as a pilot project to test the feasibility of a combined system in the Pacific islands.

The resource and energy assessments for the wind system are from wind speed readings measured at the airstrip and at the proposed site on Aitutaki. Power potential is calculated for two wind machines, a BWC Excel and a Windworks, given a range of wind speeds in meters per second, approximate midpoints of wind speeds, and frequency of

Table 5.11. Wind Speed and Output Characteristics for Two Proposed Wind Machines in Aitutaki, Cook Islands

Speed (m/sec)	Frequency (%)		Output (kW)		
Range	Midpoint	Observed[a]	Calculated[b]	BWC Excel[c]	Windworks[c]
0.0–3.1	1.6	17.1	6.9	0	0
3.1–4.1	3.6	9.6	12.2	0.2	0.2
4.1–5.1	4.6	13.1	12.9	0.7	0.8
5.1–6.2	5.6	12.6	12.5	1.3	1.9
6.2–7.2	6.7	13.1	11.0	2.3	4.0
7.2–8.2	7.7	12.1	9.1	3.5	6.1
8.2–9.2	8.7	10.6	7.1	4.6	8.5
9.2–10.3	9.7	7.2	5.2	6.1	9.6
10.3–11.3	10.8	2.6	3.4	8.0	10.0
11.3–12.3	11.8	1.1	2.2	9.5	10.0
12.3–13.3	12.8	0.6	1.4	10.0	10.0
13.3–14.4	13.8	0.2	0.8	10.0	10.0
14.4–15.4	14.9	0.1	0.4	10.0	10.0
Mean	5.8	100.0		2.33	3.41

Source: SPEC (1983, p. 13).

[a] Measured at Aitutaki airstrip, Cook Islands, meteorological office, from 1975 to 1981. Quoted in EPS project document "Grid-synchronised wind generator project" (May 1983).

[b] Frequencies calculated from Rayleigh distribution. It can be seen that this matches the observed frequencies quite well, especially in terms of the calculated output energy (Twiddell and Weir 1985, Sec. 9.6.4).

[c] Both machines have a rated power of 10 kW.

time the wind speed is observed at the site (Table 5.11). Both systems are rated at 10 kW. The observed wind speeds at the airstrip are 5.87 m/sec and at the site 7.65 m/sec.

Given a 27 percent outage factor, as discussed in a preceding section, an annual energy output (kWh) and fuel costs savings (US$/yr) can be determined (Table 5.12). Fuel savings are the current subsidized costs of producing electricity from the diesel system in the financial analysis. Given that 13¢/kWh are subsidized costs, and the Energy Mission Reports, Cook Islands (1982), estimates the full costs at NZ44.7¢/kWh or US33.5¢/kWh, the social opportunity cost savings in an economic analysis are actually higher than the private market costs shown in Table 5.12. Shipping, labor, materials, and supervisory

Table 5.12. Annual Energy Generated by Wind Generators and Resultant Diesel Fuel Savings (1983 US$)

Mean Wind Speed (m/sec) $\bar{u}$[a]	Outage[b] (%)	BWC Excel		Windworks	
		Annual MWh[c]	Fuel Savings[d] (US$)	Annual MWh	Fuel Savings (US$)
5.87	0	20.4		29.8	
5.87	27	14.9	1,900	21.7	2,800
6.5	0	24.5		37	
6.5	27	17.9	2,300	27	3,500
7.5	0	27.9		44	
7.5	27	20.4	2,700	32	4,200

Source: SPEC (1983, p. 13).

[a] Figures for $\bar{u} = 6.5$ and 7.5 m/sec calculated from Rayleigh distribution, since it gave good match to observations at $\bar{u} = 5.8$ m/sec.

[b] 27 percent outage is the average of five systems of 9–10 kW at U.S. farms monitored for one year, reported in "WPL's Wind Energy Test Programme," *Alternative Sources of Energy*, Dec. 1982, 16–19 (range was 21–31 percent).

[c] New Zealand office estimates that wind speed at the site is 1.3 times that at the airstrip, allowing for extra height by $u/u_0 = (h/h_0)^{1/7}$.

[d] Fuel savings calculated at price of NZ$0.57/liter = US$0.42/liter and reported consumption of 0.30 liter/kWh (which sounds fairly low for small diesels; large diesels of FEA (Fiji) average 0.26 liter/kWh).

costs must be added to determine the capital costs of the wind machine equipment; these capital costs are annualized into a financial annual cost analysis in Table 5.13.

Table 5.14 compares the wind-supplemented system (WSS) with the existing diesel (DS) system in a financial analysis. Wind-supplemented capital costs are left out of the bottom analysis if the system is aid-sponsored. When adding in capital costs, assuming replacement cost recovery, the comparative costs of WSS to DS are US66.2¢/kWh to US51.1¢/kWh, respectively. Any advantage of the wind-supplemented system over the existing diesel system may exist when only operation and maintenance (O+M) costs are compared, US37.1¢/kWh to US36.9¢/kWh, respectively. This unfavorable cost comparison is due to a small diesel fuel replacement (3 percent) by the wind system. Given that data on the machine's O+M and even capital costs are based primarily on manufacturer estimates which are usually too low, this wind-supplemented system cannot be seen as cost-saving for the electric authority.

Table 5.13. Estimated Capital Costs of Two Proposed Wind Systems on Aitutaki, Cook Islands

Item	Rough Estimate (US$)
Wind system (including tower)	25,000
Control equipment to connect to grid	5,000
Shipping (to Rarotonga and then to Aitutaki)	1,000
Erection materials and labor	500
Consultant's supervision (2 days)[a]	1,600
Total (estimate)	33,000
Annual capital charge (10 years, 10%)[b]	5,280
Unit costs (annual capital charge/kWh)[c]	0.20

Source: SPEC (1983, p. 13).

[a] Includes overseas travel if necessary.

[b] Calculated at

$[i\,(1 + i)^N] \div [(1 + i)^N - 1] \times [\text{capital cost}]$

$= 0.1(1.1)^{10}/[(1.1^{10}) - 1] \times \$33{,}000$

$= 0.16 \times \$33{,}000$

[c] Calculated at $5,280/27,000 kWh assuming 6.5 m/sec mean speed, 27% outage.

Even when a marginal annual cost analysis is made (Table 5.15), the WSS is financially unattractive even if capital costs are excluded; i.e., negative net marginal benefits occur even if the project receives outside funding and the pricing authority does not include capital replacement costs. In contrast, if an economic marginal cost analysis is made using the actual cost of electricity production (US33.6¢/kWh) in the Cook Islands, then the annual benefits are US$9,070, which creates positive net incremental benefits even if capital costs are excluded (US$4,370/yr). The crude economic and financial analyses suggest the wind-supplemented system will be more important for its demonstration rather than its economic potential.

ELECTRICITY PRICING

Electricity generation is a critical component of any energy plan because of its high-quality end uses. Expansion of the electrical grid or installation of village generators, gasifiers, or solar photovoltaic

Table 5.14. **Annual Average Cost Estimation for a Proposed Wind-supplemented Diesel System Versus a Diesel System in the Cook Islands (1983 US$)**

	Wind and Diesel				Diesel	
			Total			
Annual Cost	Wind (US$/yr)	Diesel (US$/yr)	(US$/yr)	(US¢/kWh)[a]	(US$/yr)	(US¢/kWh)[a]
WITHOUT AID FOR CAPITAL						
Capital	94,800[b]	89,500	184,300	29.1	89,500	14.1
Operations and maintenance						
Fuel[c]	na	107,800	107,800	17.0	111,300	17.6
Labor/travel	na	56,000	56,000	8.8	56,000	8.8
Maintenance/materials	4,700[d]	66,800	71,500	11.3	66,800	10.5
Total operations and maintenance			235,300	37.1	234,100	36.9
Total costs			419,600	66.2	323,600	51.1
WITH AID FOR WIND CAPITAL						
Capital		89,500	89,500	14.1	89,500	14.1
Operations and maintenance	4,700	230,600	235,300	37.1	234,100	36.9
Total costs			324,800	51.3	323,600	51.1

Source: Adapted from SPEC (1983, p. 17).

[a] Total electricity production is 633,500 kWh/yr.

[b] Capital costs for wind system are: powerhouse and equipment at US$330,000 with 10-year life; reticulation at US$334,000 at 25-year life; and wind machine at US$33,000 at 10-year life, assuming a 10 percent per year interest rate. Assumes 1983 costs for equipment.

[c] Assumes 13¢/kWh costs for diesel electricity, 74 percent efficiency for diesel system, thus 856,100 kWh input energy needed, and 27,000 kWh diesel fuel savings (Table 5.12).

[d] Maintenance assumes 5 percent of wind system's capital expenditure.

Table 5.15. Marginal Annual Costs and Benefits from the Addition of a Wind Generator[a] (1983 US$)

Item	Costs (US$)	Benefits (US$)
Capital	94,800	na
Extra maintenance	4,700	na
Total	99,500	
Fuel saved		3,500
Excess of benefits over costs:		
Including capital cost	-96,000	
Excluding capital costs	-1,200	

Source: Adapted from SPEC (1983, p. 19).

[a] Where marginal is defined as the difference in costs or benefits between the wind-supplemented and the diesel systems (Table 5.14).

systems have high visibility and important socioeconomic impacts (Bowman 1985). One important aspect of electricity production is estimating production costs and establishing a rate or tariff structure. This section briefly discusses important cost and policy considerations which are needed to estimate full production costs or establish reasonable tariffs for electricity.

Many technologies that can produce electricity have been described in this manual thus far; these include biogas connected to gas turbines, gasifiers connected to gas turbines, solar photovoltaic systems, hydro power, and wind energy systems. Since only the technology's financial production costs were discussed earlier, the critical issue facing energy planners is pricing the electricity produced from renewable energy systems bearing in mind the existing tariff structures for alternative, usually fossil, fuels.

Electricity Economics

Three economic issues to consider with electricity are costs of production and delivery, revenue requirement, and establishment of a tariff rate structure (Turvey and Anderson 1977). Calculating the production costs is an accounting procedure that adds the total costs of electricity production (i.e., generation, distribution, and transmission). In contrast, electricity tariffs reflect a politically determined rate that includes only part of the production costs and the necessary revenue requirements to cover some percentage of total costs. Tariffs are affected by demand response to electricity prices (price elasticities), the existing user profile (percent of commercial, residential, or industrial), and the government's or utility's attitude toward subsidizing rural or urban electrification.

COSTS OF PRODUCTION

The total costs of producing electricity can be broken into two general subunits: (1) generation, and (2) distribution/transmission costs. Both categories include capital and operating/maintenance (O+M) costs. The cost components that should be included in a production cost assessment are outlined in Table 5.16. Generation capital requirements include total plant investment, prepaid royalties, preproduction costs, inventory start-up capital, land, and miscellaneous charges. These costs are capital costs plus costs paid out up to the date that service begins. O+M costs include all fuel, labor, and administration costs (Electric Power Research Institute 1982). In addition to generation costs, distribution and transmission costs are also critical to total costs. In the previous technology sections, these costs were often left out of the financial analysis. In preparing future energy strategies the energy planner should always know the full costs of production for every electricity facility to understand the net subsidies (costs of production minus tariff price per kWh) for a particular fuel-technology mix.

REVENUE REQUIREMENT

Revenues are needed to pay for the operating and capital costs of an electrical facility. Revenue requirements fall into two general categories—carrying charges and expenses. Carrying charges include return on equity, return on debt, book depreciation, income tax on the minimum acceptable return, insurance, and property taxes. The return on equity and debt are usually valued at the minimum financial return that is acceptable to the investor. Capital charges represent the obligations to debtors and stockholders involved in the investment. Such charges are not affected by the facility's level of use since these are fixed costs that must be incurred regardless (EPRI 1982).

In contrast to carrying charges, expenses are variable costs that are influenced by the level of plant use. Expenses include the daily operating, maintenance, and fuel costs; these are production costs. A more detailed description of how to estimate return on equity and debt can be found in EPRI (1982). Since this guide is based on the U.S.

Table 5.16. General Components in Electricity Production Costs

Cost Component	Comment
Generation	
Capital requirement	
Total plant investment	Includes process capital for construction, general facilities capital (roads, buildings), engineering and overhead capital, and project contingency costs (uncertainty)
Prepaid royalties	
Preproduction (start-up)	
Inventory capital (fuel storage)	
Land costs	
Operating and maintenance	
Fuel	Diesel, wood, gas, etc.
Supplementary fuel	Lubricating oils
Labor	
Administration	Consumer-related
Miscellaneous	
Distribution/transmission	
Capital requirement	
Equipment costs	Lines, poles, meters, transformers
Operations and maintenance	
Repairs	
Labor	
Administration	
Losses	Unmetered or unrecovered payments
Miscellaneous	

Source: Adapted from EPRI (1982).

utility pricing system, cost components and revenue estimation techniques used in the Pacific may be substantially different.

ELECTRICITY TARIFFS

In establishing electricity charges to individual users, referred to as tariffs, an electric authority bases the rate structure on a variety of factors. Costs of production and revenue requirements are crucial to the rate structure but are only two factors considered in the process. For instance, revenue requirements include only finance, investment, and partial production costs. Other factors considered by a utility or government agency include equity issues, incentives or expected price response (price elasticities), development objectives, and political feasibility of changing electricity prices.

For instance, a country concerned about equity may establish low rates for residential users with low levels of energy demand to ensure widespread availability among all income levels. A planning agency may also realize that the full costs of production may simply be too high to encourage use among domestic users but acceptable to encourage industrial users. Thus, separate rates for different sectors in the economy are usually charged.

Typically in the Pacific, tariff rates are set below actual production costs, in some cases far below. Given that electricity rate changes are extremely sensitive politically, price incentives in a rate structure should reflect future as well as current revenue needs. Different rate structures such as (1) a **two-tiered tariff** (a low rate for meeting the annual minimum amounts of energy needs for domestic users and a higher rate for industrial or large-scale users) or (2) a **life-line tariff** (a low rate for meeting minimum domestic needs but other rates above the minimum) are often suggested in the Energy Mission Reports (1982) for Pacific island countries. As important socioeconomic impacts have occurred from early rural electrification projects in the Pacific (Bowman 1985), planners need to be realistic about the real versus expected costs of electrification and be aware of who benefits.

By no means is this discussion sufficient for understanding the complexity of electricity pricing. However, it attempts to clarify the point that electricity economics involves a comparison of production costs, revenue requirements, and tariffs. The closer tariff rates come to meeting the full costs of production, the more economically viable the electricity facility is. In the long run, substantial subsidies that drain the national economy will be needed to support public utility facilities if planners ignore production costs.

If renewable energy sources are used to produce electricity for outer islands or even central cities, national pricing authorities will need to consider how to set the charges for renewables relative to existing diesel or hydro charges. Pricing inequity among fuels implies priorities that are not necessarily intended. Renewable energy systems often have a higher degree of start-up problems if people are unfamiliar with these systems; certainly they have more complex resource production systems in the case of forestry, agriculture, and waste use. Their project risk, therefore, may be or be perceived to be higher than the known risk in previous energy projects such as diesel generators. Pricing policies must be made with long-term strategies, not necessarily short-term goals, in mind. As always, decision makers need to be aware of the consequences of their established rates to create the energy use, mix, and conservation incentives the country desires.

APPENDICES

Appendix A. The SI and British Systems

UNITS AND PREFIXES FOR THE INTERNATIONAL SYSTEM OF UNITS (SI) AND THE BRITISH SYSTEM

		SI	British
thousand	10^3	k (kilo)	M
million	10^6	M (mega)	MM
billion	10^9	G (giga)	B
trillion	10^{12}	T (tera)	–

ABBREVIATIONS

	SI	British
Length		
	m = meter	in = inch
	cm = centimeter	ft = foot
	km = kilometer	mi = mile
Area		
	m^2 = square meter	ft^2 = square foot
	ha = hectare	ac = acre
		mi^2 = square mile
Volume		
	m^3 = cubic meter	ft^3 = cubic foot
	l = liter	B gal = Imperial gallon
		US gal = US gallon
		US bbl = US barrel
		SCF = standard cubic foot
Velocity		
	m/sec = meters per second	ft/sec = feet per second
	km/hr = kilometers per hour	mph = miles per hour
Flow		
	m^3/sec = cubic meters per second	ft^3/min = cubic feet per minute
		Mgd = million gallons per day
Mass		
	kg = kilogram	lb = pound
	MT = metric ton	t = ton
	cal = calorie	lbm = pound mass
Energy		
	J = joule	BTU = British thermal unit
	cal = calorie	BTU/hr = BTU per hour
	Wh = watt hour	
	kWh = kilowatt hour	
	eV = electron volt	

Power

W = Watt
J/sec = joules per second
Ly = Langley

BTU/hr = BTU per hour
HP = horsepower

CONVERSION FACTORS

Length (meters)[a]

1 m = 3.281 ft	1 ft = 0.3048 m
1 km = 0.6214 mi	1 mi = 1.609 km
1 cm = 2.540 in	1 in = 0.3937 cm

Area (square meters)[a]

1 m^2 = 10.76 ft^2	1 ft^2 = 0.09290 m^2
1 ha = 10 m^2	1 ac = 0.4047 ha
1 ha = 2.471 ac	1 mi^2 = 640 ac

Volume (cubic meters)[a]

1 m^3 = 6.102×10^4 in^3	1 in^3 = 1.639×10^{-3} m^3
= 10^3 liters	1 US gal = 3.785×10^{-3} m^3
= 264.2 US gal	1 B gal = 4.546×10^{-3} m^3
= 220.0 B gal	
= 35.31 ft^3	1 ft^3 = 0.02832 m^3
= 6.290 US bbl	1 US bbl = 0.1590 m^3
	1 US bbl (oil) = 42 US gal
= 0.2759 cord	1 cord = 3.625^2 m^3
	1 cord (wood) = 128 ft^3

Velocity (meters per second)[a]

1 m/sec = 3.600 km/hr	1 km/hr = 0.2778 m/sec
= 3.281 ft/sec	1 ft/sec = 0.3048 m/sec
= 2.237 mph	1 mph = 0.4470 m/sec

Flow rate (cubic meters per second)[a]

1 m^3/sec = 2,119 ft^3/min	1 ft^3/min = 4.719×10^{-4} m^3/sec
= 22.82 Mgd	1 Mgd = 0.0438 m^3/sec

Mass (kilograms)[a]

1 kg = 10^{-3} MT	1 MT = 10^3 kg
= 2.205 lbm	1 lbm = 0.4536 kg
= 1.102×10^{-3} t	1 t = 907.2 kg

Density (kilograms per cubic meters)[a]

1 kg/m^3 = 0.06243 lbm/ft^3	1 lbm/ft^3 = 16.02 kg/m^3

Energy (joules)[a]

1 J = 10^{-3} KJ
= 10^{-6} MJ
= 10^{-9} GJ

1 J = 0.23990 cal
= 9.485×10^{-4} BTU

1 cal = 4.184 J
1 BTU = 1,054 KJ
1 BTU = 252 cal

Energy (watt hours)[b]

1 Wh = 3,600 J = 3.6 MJ
1 kWh = 3,412 BTU
1 kWh = 85.99 Ly

1 BTU = 2.93×10^{-4} kWh
1 Ly = 0.01163 kWh/m^2

Power (watts)[a]

1 W = 1 J/sec
= 3.414 BTU/hr
= 0.03156 GJ/yr
= 1.340×10^{-3} HP

1 BTU/hr = 0.2929 W
1 HP = 746 W

Power (Langleys, BTUs)[c]

1 Ly/hr = 11.6277 W/m^2
1 Ly/min = 697.4 W/m^2
1 Ly/min = 1 cal/cm^2 · min
1 BTU/ft^2 = 3.154 Wh/m^2
1 BTU/ft^2 = .2713 Ly
1 MJ/m^2 = 88.1 BTU/ft^2

Solar constant (energy flux)[a]

1.353 kW/m^2
1.94 Ly/min
116.4 Ly/hr
428 BTU/hr · ft^2

Energy Unit Matrix[b]

	is equal to				
1 joule	1 joule	2.39×10^{-4} kcal	9.48×10^{-4} BTU	2.78×10^{-7} kWh	6.25×10^{18} eV
1 kilocalorie	4186 joules	1 kcal	3.97 BTU	1.16×10^{-3} kWh	2.62×10^{22} eV
1 British thermal unit	1055 joules	0.252 kcal	1 BTU	2.93×10^{-4} kWh	6.59×10^{21} eV
1 kilowatt-hour	3.6×10^{6} joules	860 kcal	3413 BTU	1 kWh	2.25×10^{25} eV
1 electron-volt	1.60×10^{-19} joules	3.82×10^{-23} kcal	1.52×10^{-22} BTU	4.45×10^{-26} kWh	1 eV

Sources: [a] Socolow (1978, Appendix D, pp. 311–14).
[b] Thorndike (1976, Appendix E).
[c] Schaller and Larson (1983, p. B-6).

Appendix B. Moisture Content

The water content in a fuel affects the fuel's input energy since all water must be evaporated before energy can be available for other purposes. Two forms of water exist–the water in the fuel before combustion (existing water) and water formed during combustion from a fuel's elemental hydrogen and atmospheric oxygen. The existing water content in a fuel is often referred to as the "surface" water. When estimating the fuel's input energy, we need to account for the heat of vaporization consumed in evaporating both existing or formed water when wet (not oven-dried) fuel is burned. If any moisture exists in a fuel at the time of combustion, the fuel's wet weight and LHV must be multiplied to determine the input energy available from the fuel.

Moisture content can be calculated either on a wet basis (mcwb) or a dry basis (mcdb). Only mcwb is used in this manual, but the following equations allow data conversions between the two methods (Earl 1975).

$$\text{mcbd} = \frac{\text{Water Weight of Fuel}}{\text{Dry Weight of Fuel}} \times 100\% = \text{D}\% \tag{B.1}$$

$$\text{mcwb} = \frac{\text{Water Weight of Fuel}}{\text{Wet Weight of Fuel}} \times 100\% = \text{W}\% \tag{B.2}$$

where Wet Weight = Dry + Water Weight

It is extremely important to distinguish which moisture content system is associated with a given energy value, because the two systems have different scales. For example, if a fuel has 50 percent water and 50 percent combustible material (ignoring possible ash content), then in the mcwb system the moisture content is given as 50 percent mcwb. However, in the mcdb system, the same piece of wood has a moisture content of 100 percent mcdb. Equations for converting between these systems are:

$$\text{D} = [\text{W}/(1 - \text{W})]/100 \tag{B.3}$$

$$\text{W} = [\text{D}/(1 + \text{D})]/100 \tag{B.4}$$

where W = 40 if 40 percent mcwb is used

For example, suppose an analyst calculates the wet piece of fuelwood to have 0.60 kg solid wood (dry) and 0.40 kg water. The fuel's moisture content is 40 percent mcwb (0.4 kg/0.6 + 0.4 kg) or 66 percent mcdb (0.4 kg/0.6 kg).

A further complication is that all fuels (biomass and fossil fuels) differ in their average moisture contents. Biomass fuels taken from fields have more than 60 percent mcwb in the humid tropics such as the Pacific, but when allowed to air dry, their equilibrium moisture contents may significantly drop to between 20 and 25 percent mcwb.

Three common but often misleading terms used to distinguish the moisture content of a fuel are (1) oven dried, (2) green, and (3) air dried. Oven dry (od) refers to the fact that no surface water exists in the fuel. High heating values are given on an oven-dry basis. Green refers to the moisture content in a fuel at the time of harvest (i.e., before it has been air dried). In the Pacific, moisture contents up to 65 percent mcwb have been found for some wood species, although they more typically run from 40 to 55 percent mcwb depending on the local rainfall. Although the term wet wood is often used to mean green wood, it actually includes both green or air-dried fuels. Air dried refers to the moisture content of a fuel after it has been left outside to dry.

The crucial and confusing fact is that except for oven dry (0% mcwb or mcdb), neither air-dried nor green moisture content refers to a unique moisture content. Air-dried wood on an atoll or leeward side of an island may have a far lower moisture content (10–20% mcwb) than wood in the humid or windward regions (20–35% mcwb). Thus, when energy values are reported as "15 MJ air dried," the analyst must always ask at what specific moisture content the calculation was made. Air dried means nothing by itself; only "15 MJ air dried at 15 percent mcwb" tells the analyst the full information needed to make reasonable energy calculations.

Appendix C. Formulas and Selection Criteria for Project Analysis

Decision Criteria	Formulas	Selection Criteria (accept project if the following are met)
Break-even	find b_{tj} or c_{tj} so that $\sum_{t=0}^{n} \frac{B_t}{(1+i)^t} = \frac{C_t}{(1+i)^t}$ where $B_t = b_{t1} + b_{t2} + \ldots b_{tj} = \sum_{j=1}^{h} b_{tj}$ $C_t = c_{t1} + c_{t2} + \ldots c_{tj} = \sum_{j=1}^{h} c_{tj}$	b_{tj} or c_{tj} = value for a benefit (b_{tj}) or cost (c_{tj}) which sets total benefits (B_t) in year t equal to total costs (C_t), where t = time interval (year); j = individual benefit (b) or cost (c) in year t; and Σ refers to summing over years 0 to n, and benefits or costs 1 to h.
Net present value (NPV) or discounted benefits − costs (B − C)	$\sum_{t=0}^{n} \frac{B_t}{(1+i)^t} - \sum_{t=0}^{n} \frac{C_t}{(1+i)^t} = NPV$	$NPV \geqslant 0$, where positive net benefits exist.
Incremental net benefits (Δ discounted B − C)	$\underbrace{\sum_{t=0}^{n} \frac{(B_t - C_t)}{(1+i)^t}}_{\text{project 2}} - \underbrace{\sum_{t=0}^{n} \frac{(B_t - C_t)}{(1+i)^t}}_{\text{project 1}} = \Delta NPV$	$\Delta NPV \geqslant 0$, choose project 2 over project 1 if the incremental net benefits going from project 1 to 2 are positive.
Benefit-cost ratio (B/C)	$\frac{\sum_{t=0}^{n} \frac{B_t}{(1+i)^t}}{\sum_{t=0}^{n} \frac{C_t}{(1+i)^t}} = B/C$	$B/C \geqslant 1$, choose the project so long as the ratio of project benefits to costs is greater than 1.

Simple payback period[a] (nondiscounted)	find year t: $\sum_{t=0}^{n} (B - O)_t = K$	$t \leqslant$ payback year in alternative project, choose the project, if the payback year ($1 \leqslant t \leqslant n$) is acceptable to investor and less than or equal to the payback period of an alternative investment.
Discounted payback period[a]	find n: $\sum_{t=0}^{n} \frac{(B - O)_t}{(1 + i)^t} = K$	same as above.
Internal rate of return (IRR)	find r: $\sum_{t=0}^{n} \frac{(B - C)_t}{(1 + r)^t} = 0$	$r_1 \geqslant r_2$, r_2 for best alternative investment, choose the project if the rate of return of project 1 is greater than or equal to the rate (r_2) of the best alternative investment.
Cost effectiveness	$\dfrac{\sum_{t=0}^{n} \frac{C_t}{(1 + i)^t}}{\text{Nonmonetary benefits (units)}}$	C/unit benefit is socially acceptable.

Source: Adapted from Mishan (1983) and Gittinger (1982).

Note: $B_t = \sum_{j=1}^{h} b_{tj}$, the sum of project benefits ($j=1 \ldots, h$) over time t (t=time $0 \ldots, n$); $C_t = \sum_{j=1}^{h} c_{tj}$, the sum of project costs ($j=1 \ldots, h$) over time t; O = operating costs; K = initial capital costs; Σ = summation of variables; i = discount rate; r = rate of return; and n = project time period n.

[a] Simple payback period, although too often used, is incorrect decision criteria if the project year is greater than 1. A discounted payback period should always be used in projects with lives extending beyond one year.

Appendix D. Energy and Production Characteristics for Various Tree and Palm Species

Scientific Name	Annual Average Yield (m³/ha·yr)	Average Rotation Length (yrs)	Possible Regeneration[a]	Nitrogen Fixing[b]	Use Priority[c]	Specific Gravity[d] (s.g.)	HHV[e] (MJ/od kg)
Acacia auriculiformis	10–20	8–12	S, C	Y	F	0.60–0.80	17.7–20.3
Acacia decurrens	17	8	S, C	–	F	–	18.7
Acacia farnesiana	–	–	S, C	–	F	0.84	19.2
Acacia leucopholea	19	20	S, C	–	F	–	21.8
Acacia mangium	30	–	S, C	Y	F	0.65	–
Acacia mearnsii	10–25	7–10	S, C	Y	F	0.70–0.85	16.7–19.3
Albizia falcataria	30–40	5–15	S, C	Y	P, T, F	0.33	18.1
Albizia lebbeck	5	10–15	S, C	Y	T, F	0.55–0.60	21.8
Albizia procera	–	–	S, C	Y	T, F	0.66	19.7
Alnus nepalensis	10–20	15–20	S, C	Y	F, P	0.32–0.37	16.0–18.3
Alstonia macrophylla	–	–	S	N	P, T	0.56	19.2
Anthocephalus cadamba	15	9	S	N	P, T	0.33	18.9–19.8
Antidesma ghaessimbilla	–	–	–	–	–	0.60	19.1
Avicennia officinalis	–	–	S	–	F	0.63–0.70	18.5
Bruguiera gymnorrhiza	5–10	30	S	–	T, F	0.70–1.00	20.4
Bruguiera parviflora	5–10	30	S	–	F	0.70–1.00	18.7
Bruguiera sexangula	5–10	30	S	–	F	0.81	19.4
Calliandra calothyrsus	10–20[f]	1	S, C	Y	F, T	0.51–0.78	18.9–19.9
Cassia fistula	–	–	S, C	N	T, F	0.52	18.4
Cassia siamea	10–15	5–10	S, C	N	F, T	0.60–0.80	18.8
Casuarina equisetifolia	5–15	7–10	S	Y	T, F	0.80–1.20	19.0–21.1
Ceriops tangal	–	–	S	–	F	0.81	19.6

Cocus nucifera	–	–	S	N	T, F		19.0
Cordia dichotoma	–	–	S	–	T	0.66	18.4
Dalbergia latifolia	15	20	S, C	Y	T	–	19.8
Dalbergia sissoo	–	–	S, C	Y	T	0.68	19.0–21.0
Derris indica	10–15	4–5	S, C	N	T, F	–	19.3
Diospyros philippinensis	–	–	S	N	T	0.75	18.6
Diospyros philosanthera	–	–	S	N	T	0.58	18.1
Eucalyptus camaldulensis	17–35[g]	7–10[g]	S, C	Y	T, F	0.43	19.0–21.0
Eucalyptus deglupta	–	–	S, C	Y	P, T, F	0.43	18.7
Eucalyptus globulus	10–30	5–15	S, C	Y	T, F	0.80–1.00	20.1–21.0
Eucalyptus grandis	17–60	6–10	S, C	Y	T, F	0.40–0.55	19.0–20.5
Eucalyptus urophylla	19	9	S, C	Y	F, T	–	–
Gigantochloa apus	15	5	S	–	–	–	18.4
Gliricidia sepium[h]	8–20	8	S, C	Y	P, F	0.74	19.0–20.6
Grevillea robusta	15	10–15	S	–	T, F	0.57	–
Grewia multiflora	–	–	S	–	–	0.45	–
Inga vera	–	3–5	S, C	N	–	0.57	–
Lagerstroemia speciosa	10	15	S	N	T	0.59	19.3
Leucaena diversifolia	25	–	S, C	Y	T, F	0.54	–
Leucaena leucocephala	30–40[i]	5–10[i]	S, C	Y	F, T	0.53–0.58	17.5–19.5
Prosopis pallida	8	–	S	N	F	0.80	19.0–20.5
Pterocarpus indica	10	15	S, C	Y	T, F	–	–
Rhizophora apiculata	5–10	30	S	Y	T, F	0.70–1.00	20.1
Rhizophora mucronata	5–10	30	S	Y	T, F	0.70–1.00	21.3
Samanea samau	15	–	S, C	Y	T, F	0.52	–
Schima noronhae	5–12	8	S	–	–	–	20.0
Schleichera oleosa	10	25	S	–	–	–	18.7
Sesbania glandiflora	15–25[j]	3–7[j]	S, C	Y	F	0.42	19.3

Appendix D. *(continued)*

Scientific Name	Annual Average Yield (m^3/ha·yr)	Average Rotation Length (yrs)	Possible Regeneration[a]	Nitrogen Fixing[b]	Use Priority[c]	Specific Gravity[d] (s.g.)	HHV[e] (MJ/od kg)
Swietenia macrophylla	17	25	S, C	N	T	–	20.7
Syzygium cumini	–	–	S, C	N	F	0.77	20.1–20.5
Tamarindus indica	5	25	S, C	Y	T, F	–	–
Terminalia catappa	10–15	10–15	S	N	F	0.59	–
Trema orientalis	10	8	S, C	N	F	0.25	–
Xylocarpus granatum	–	–	S	N	–	0.56	16.3
Xylocarpus moluccensis	–	–	S	N	–	0.58	15.4
Zizyphus talanai	–	–	S	N	–	0.69	18.3

Sources: Adapted from the University of Philippines (1981) and NAS (1980).

Notes: Characteristics are presented for more than 60 trees or palms that have been or may be used as energy sources. However, many species also have alternative or better uses, such as timber. The values in the table above are not always comparable; since data come from a variety of studies, uniformity of measurements and consistency of definitions cannot be assured. Some data are based on small species trials, making these data only instructive, not definitive. Great care needs to be taken, especially with air-dry density and calorific value estimates. Unfortunately, the moisture content for the air-dry weight was usually not given in most research. Calorific values generally are assumed to be high heat values—oven-dry energy contents. Rounding errors and varying measurement conditions, however, make the data on HHV suggestive at best. These problems may not be too critical to rough estimates since energy contents do not vary widely among most species. An average "wood" value often used is 15 MJ/kg at 15 percent mcwb, or 13 MJ/kg at 25 percent mcwb. The table does not mean to suggest that every species be used as fuelwood; it merely gives particular characteristics.

[a] Regeneration code: C means tree can be coppiced; S means that regeneration is primarily from seeds or plantings.

[b] Nitrogen-fixing code: Y means that the plant has the ability to fix nitrogen and thereby will enrich the soil; N means that the plant does not fix nitrogen.

[c] Use priority provides a hierarchy of uses for the plant, with P indicating pulpwood, T timber, and F fuelwood. The typical ranking of use priority is indicated by the order of the symbols, although priority may change among different users.

[d] Specific gravity is related to basic density as: Basic Density (od kg/m^3) = (Specific Gravity) (1,000 od kg/m^3).

[e] HHVs may vary by ±10–20 percent.

[f] Average yields for *Calliandra calothyrsus* often increase to 30–65 m^3/ha · yr after the first cutting at six months to a year.

[g] Values are given for good sites; poor, dry sites average 2–11 m^3/ha on a 10–14 year rotation.

[h] Also known as *Gliricidia maculata.*

[i] Well-managed plantations of giant *L. leucocephala* report 50–100 m^3/ha · yr on a 3–5 year rotation.

[j] Data for well-managed plantations.

Appendix E. Production of Various Livestock and Human Waste (based on U.S. data)

	Live Weight (lb)	Wet Raw Manure[a]			Total Solids		Volatile Solids
		lb/day	ton/yr	gal/day	lb/day	ton/yr	lb/day
Bovine							
Dairy cow	1,600	132	24	18	16.6	3.1	13.8
	1,300	107	19.5	15	13.5	2.5	11.2
Dairy heifer	1,000	85	15.5	11.2	9.2	1.7	7.5
Beef feeder	1,000	60	11	7.5	6.9	1.3	5.9
Beef stocker	500	45	8.2	5.2	5.8	1.0	4.8
Horse							
Large	1,000	45	8.2	6.7	9.4	1.7	7.5
Medium	850	36	6.6	5.4	7.0	–	5.5
Pony		15.4	–	–	3.0	–	2.4
Swine							
Hog breeder	500	25	4.6	3	2.2	0.4	1.6
Hog feeder	200	13	2.4	2.2	1.2	0.22	1.0
	100	6.5	1.2	1.1	0.6	0.11	0.5
Piglet	15	1.0	0.2	–	0.1	–	–
Sheep							
Feeder	100	4	0.7	0.8	1.0	0.18	0.8
Lamb	30	1.5	0.3	–	0.4	–	0.2
Fowl							
Geese, turkey	15	0.6	220 lb	0.2 qt	0.15	55 lb	0.10
Ducks	6	0.4	250 lb	0.15 qt	0.10	37 lb	0.07
Broiler chicken	4	0.3	110 lb	0.1 qt	0.07	26 lb	0.05
Laying hen	4	0.2	75 lb	0.1 qt	0.05	18 lb	0.04

	Portion	Amount	Total Solids		Volatile Solids	
			%	lb/day	%	lb/day
Humans (150 lbs)	Urine	2 pt., 2.2 lb	6	.13	75	.10
	Feces	0.5 lb	27	.14	92	.13
	Total	2.7 lb	11	.27	84	.25

Source: Adapted from Merrill and Gage (1978, Table 1, p. 198).

[a] Bulk density of raw manure = 34 ft^3/ton, or 60 lb/ft^3, or 8 lb/gal, with no flushing water.

Appendix F. Turbines

Pelton wheel

For medium- and high-head micro-hydro systems, the Pelton wheel is commonly used. It offers simplicity, ruggedness, and insensitivity to foreign material in the water. Its characteristics include a high starting torque and a high efficiency level when operated within its relatively narrow design power range. In a Pelton wheel, the water is passed through a nozzle to increase its speed. The water stream is directed into buckets on a wheel and the force of the water on the buckets causes the wheel to rotate.

For most efficient operation, the Pelton turbine must be designed to fit the net head of the site and its expected load. Turbine efficiency is reduced when either greater than design loads or smaller than design loads are applied. In general, the higher the head, the greater the efficiency, though the increase is nominal for heads above 100 meters. The rotational speed of the Pelton wheel is low for units larger than a few kilowatts, and low-cost alternators must usually be driven through a gear box, belt, or chain drive to rotate fast enough.

Turgo turbine

Operating on a principle similar to the Pelton wheel, the Turgo turbine allows the water jet to be directed from the side rather than tangent to the wheel, so a large jet can hit several blades at once (in a Pelton wheel, only one cup at a time is in the jet). This provides more power in a smaller wheel and a smoother, low-vibration power source. The Turgo turns faster to produce the same power, often allowing alternators to be driven without belts, chains, or gears. The Turgo is more sensitive to foreign matter in the stream than is the Pelton wheel. The construction of the Turgo turbine is more complex and is generally more expensive than the Pelton.

Cross-flow turbine

The term cross flow, referring either to a Michell or Bianki turbine, comes from the water crossing the turbine and hitting the blades twice. Since the diameter of the wheel determines the head at which the unit performs most efficiently and the length of the wheel determines the power level at which the unit performs most efficiently, a long wheel can accommodate a wide range of loads efficiently by having more or less of its length in the water flow. The cross-flow turbine also has a higher turning rate than either the Pelton or the Turgo and can be designed to directly drive alternators. Control of the rotational speed of the cross flow unit is more easily accomplished than with either the Pelton or the Turgo turbine.

Francis turbine

The Francis turbine accepts water around its circumference and passes it out along its axis. The Francis can be designed to meet the needs of virtually any head. It provides reasonable efficiency over a range of loading. Its cost tends to be higher than Pelton or Turgo wheels since the rotor must be carefully fitted to the inlet ring (called a wicket gate). The unit is relatively fragile and can be easily damaged by rocks or abrasive matter carried through the inlet water. It can drive alternators directly. The starting torque is moderate but the operating torque is high. The speed of the unit is usually controlled by changing the angle of the inlet stream. Although Francis turbines are commercially available in micro-hydro size ranges, they are not common.

Propeller turbine

The propeller turbine is designed for high flows at low heads. It is much like a ship's propeller in appearance although it usually is enclosed in a duct to improve efficiency. This is an axial-flow type of turbine. For low powers, the blades are usually fixed to the shaft, although this limits the unit to best efficiency over a narrow range of flows. High-power propeller turbines may have adjustable blades to allow high-efficiency operation over a wider range of conditions. Since large flows pass through these turbines, they are sensitive to the presence of abrasive materials and debris in the water. Speed control of fixed blade units is more difficult than most turbine types. Systems that place constant loads on the turbine appear most cost effective when sufficient water is available to maintain constant flow conditions.

Kaplan turbine. The Kaplan turbine is a variable-pitch propeller turbine with an inlet using adjustable gates as the Francis turbine does. The gates and the blade pitch are coordinated automatically, resulting in very efficient operation over a wide range of flow and head conditions. These units are not found in small hydro installations because of their control complexity and cost.

Bulb turbine. One of the problems of the propeller turbine is the placement of the alternator. Since the water flows along the drive shaft, the shaft or the water flow must be curved to allow placement of the alternator out of the water. The result is a long drive shaft and a curbed water channel, which is expensive and introduces head losses. The bulb installation places the generator in the water flow by mounting it inside a waterproof, streamlined bulb upstream of the propeller. Shorter tailraces and less complex civil works result though special attention must be given to the removal of heat from the alternator and waterproofing the housing. Small bulb units are available for micro-hydro service in low head, high-flow installations. In a site with an irrigation dam, for example, excess flows directed through a bulb unit using a 3-meter head could provide 10 kW with a flow of 525 liters per second. The small units have fixed blades and speed control is difficult except with constant load control systems.

Other turbine types

Excluded from this discussion are all types of open water wheels historically used for mechanical power production. Their best application is with low heads on large streams, which are uncommon in the Pacific. Not only are they less efficient than the turbines listed above, they also are particularly susceptible to flooding. Also, the wide range between low and maximum flows of Pacific island streams makes their installation expensive due to the long diversion channels necessary. Water wheels should not be part of a priority development program in most of the Pacific although they may be useful at some sites for the production of mechanical power in the 0- to 10-kW range. Exotic water conversion systems such as the venetian blind version of a cross-flow unit (e.g., the Schneider hydronamic power generator), have not been adequately tested in the field and should not be used in developing countries until successful field tests of five or more years are complete and units are commercially available at competitive prices.

Source: Adapted from Merrill and Gage (1978).

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INDEX

Agricultural resources, assessing feasibility of, 68. *See also* Crop residue resources; Crop resources

Air-dried weight, 10, 200–201

Amortization, 28

Annual cost analysis, 22

Appropriateness index, 20

Average cost analysis, 31

B/C. *See* Benefit/Cost ratio

B - C. *See* Benefits minus costs

Before and after method. *See* Project comparisons

Benefit/Cost ratio, 33

Benefits, in valuation measures, 23

Benefits minus costs, 32

Benefits and costs, as valuation measures, 24

Biomass resources, 38. *See also* Charcoal resources; Crop residue resources; Crop resources; Forest residues; Forest resources, nonsustainable; Forest resources, sustainable; Wastes, animal or solid

Break-even analysis, 32

Capital, 27–29

Carbonization. *See* Charcoal resources; Charcoal technology

Cash values. *See* Private market values

Charcoal resources: advantages and limitations, 82; data, 84; equations, 83; examples, 83–84; sources, 82; transport costs, 82; uses, 79, 82

Charcoal technology: conversion efficiency, 127–28; data, 128–29; economics, 129; equation, 127–28; example, 129–31; kilns, 126–31; retorts, 127. *See also* Kilns, charcoal

Compounding factor, 25

Conversion efficiencies, 12–14; general equations and example, 13–14; stove equations and data, 121–24; charcoal kiln equations and data, 127–28; biogas digestor equations and data, 134–35; gasifier system equations and data, 141–43; solar photovoltaic equations and data, 156, 159; solar thermal data, 152; wind equations and data, 179

Controlled cooking test. *See* Stove technology: efficiency tests

Cost-effectiveness: as method of social accounts, 20; as decision criterion, 34

Costing, types of, in project analysis, 18, 19. *See also* Average cost analysis; Marginal cost analysis

Costs, in valuation measures, 23

Crop residue resources, 69; data, 75–76; definitions, 72–73; equations, 71–72; example, 73, 74

Crop resources: data, 75–76; definitions, 69–70; equations, 69; example, 70–71

Data: animal or solid wastes, 79; charcoal, 84; charcoal kilns, 128–29; crops and crop residues, 75–76; forestry, nonsustainable, and forest residues, 59–63; forestry, sustainable, 47–52; gasifiers, 143; stoves, 123–24; wind, 109–15

DCF. *See* Discounted cash flow analysis

Decision criteria, in project analysis, 18, 19, 32–34, 202–3

Depreciation, 28

Digestors, biogas: benefits, 131; conversion efficiencies, 134–35; data, 134–35; definitions, 134–35; equations, 133–34; example, 136–38; problems, 131–32; technology, 132, 135–36

Discounted cash flow analysis, 22–23

Discounted net benefits. *See* Net present value

Discounted payback period, 33

Discounting factor, 25–26

Discount rate, 22; private versus social, 26–27; in compounding or discounting, 26

Economic analysis, 20; benefits and costs in, 29; capital in, 29; foreign exchange factor in, 29, 30; in market perspective, 20; taxes and transfer payments in, 29–30; valuation in, 20–21

Economics, energy system: biogas digestors, 136; charcoal, 129; electricity, 189–90; gasifiers, 145; hydro, 172–75; solar, 160; stoves, 124–26; wind, 184

Electricity: economics, 189–90; pricing, 187, 189, 193; production costs, 190, 191; revenue requirement, 190; tariffs, 191–93

End-use matching, in energy planning, 15–16

End-use profile, of fuel, 2

Energy: assessment components, 5; conversion factors, 198–99; definition, 7; equation, 7; measurement units, 7, 197–98; planning, 2; transformation stages, 6

Energy content: animal or solid wastes, 79, 80–81; charcoal, 79–82, 84, 126; coconut residues, 62; crops, 70, 74–75; crop residues, 73, 74–75; forest residues, 60–61; forestry, nonsustainable, 54, 60–61; forestry, sustainable, 44, 47–48; gas, 143–45, 146–47

Energy, input, 5, 8; calculating, 8–10; example, 10–11; estimating, 9

Energy, output. *See* Energy, usable

Energy Mission Reports, 1, 3

Energy, usable, 5; estimating, 12–13

Environmental impact statement, 20; in market perspective, 20, 21; types of impacts, 20–21

Equations, general: capital recovery factor, 28; compounding factor, 25; current interest rate, 26; depreciation, 28; discounting factor, 26; energy, 7; foreign exchange shadow value, 29; gross energy efficiency, 13; high heat value to low heat value, 8; low heat value to high heat value, 8; moisture content wet basis, 8, 10; net energy efficiency, 13; power, 7

Equations, resource: animal or solid wastes, 79; charcoal, 83; crop residue, 71–72; crops, 69; forest residues, 56–59; forestry, nonsustainable, 53; forestry, sustainable, 41–42, 45; hydro, 96–97, 100; solar, 89, 90, 91; wind, 108

Equations, technology: biogas digestors, 133–34; charcoal kilns, 128; gasifiers, 140–43; hydro, 165; solar photovoltaics, 155–57; stoves, 119–21; wind, 175, 176

Examples, general: input energy, 10–11; gross energy efficiency, 13; net energy efficiency, 13; energy supply needs, 14–15; benefits and costs with financial market perspective, 30–31

Examples, resource: animal or solid wastes, 79; charcoal, 83; crop residues, 73–74; crops, 70–71; forest residues, 59; forestry, nonsustainable, 54–55; forestry, sustainable, 45–46, 63–68

Examples, technology: biogas digestors, 136–38; charcoal kilns, 129–31; gasifiers, 146, 148; hydro, 165–66, 173–75, 179, 180; solar, 160–62; stoves, 121–23; wind, 184–87

Field surveys, for wind resources, 114

Financial analysis, 19–20; benefits and costs in, 29; capital in, 29; in market perspective, 19–20; valuation measures in, 20–21, 24

First Law of Thermodynamics, 12. *See also* Gross energy efficiency

First-year cost analysis, 22

Foreign exchange factor, 29

Forestry potential, sustainable versus nonsustainable, 39–40

Forest residues, 55; data, 59–61, 63; energy content, 60–61; equations, 56–59; example, 59; moisture content, 60–61

Forest resources, nonsustainable, 39, 52; data, 59–61; definitions, 53–54; equations, 52–53; example, 54–55

Forest resources, sustainable, 39; data, 47–52; definitions, 42–44; economics, 64, 66–67, 68; equations, 42; example, 45–47; factors affecting use, 40–41; management schemes, 44–45; species characteristics, 50–52, 204–7; species selection criteria, 48–49

Gasifiers, 139; conversion efficiencies, 141–43; data, 143; drawbacks, 139; economics, 145; energy content, 143–45, 146–47; equations, 140–43; examples, 146, 148; renewed interest in, 138–39; technology, 139

Green weight, 10, 200–201

Gross energy efficiency, 13–14

High heat value, 8; calculating from low heat value, 8

Hydro resources, 94; definitions, 95–96, 100–101; equations, 96–97, 100; mapping, 97–99; study priorities, 99–100; surveys, 101–106

Hydro technology: components, 163, 165; definitions, 163–64; economics, 172–73; electrical generation, 168–70; equations, 165; examples, 165–66, 173–75; intake systems, 166–68, 171; powerhouse, 171; turbines, 170, 210–12

Impound systems. *See* Hydro technology: intake systems

Incremental cash flow. *See* Incremental net benefit

Incremental net benefit, 33

Inflation, 26, 27

In-kind transfers. *See* In-kind values

In-kind values, 24

Input energy. *See* Energy, input

Interest rates: according to discounted cash flow, 27; current versus real, 26

Internal rate of return, 33–34

Kilns, charcoal: conversion efficiencies, 127–28; efficiency, 127; energy content, 126; Philippine oil drum method, 126–27; production and technology, 126; Tongan oil drum method, 27. *See also* Charcoal technology

Kitchen performance test. *See* Stove technology: efficiency tests

Law of Conservation of Energy. *See* First Law of Thermodynamics

Life-line tariff, 192

Low heat value, 8, 10; calculating from high heat value, 8

Marginal cost analysis, 31

Market perspective, in project analysis, 18–21. *See also* Financial analysis; Economic analysis

Moisture content, 8; calculation methods, 200–201; crop residues, 73; crops, 70; forestry, nonsustainable, 60–61; forestry, sustainable, 60–61; and low heat values, 11

Moisture content wet basis, equation, 8, 10

NDCF. *See* Nondiscounted cash flow analysis

Net energy efficiency, 13–14

Nondiscounted cash flow analysis, 22n

Oven-dry weight, 10, 200–201

Power: conversion factors, 198–99; definition, 7; equation, 7; units, 7, 198

Private market values, 23

Project analysis, 17; defining goals in, 18; economic tools of, 18, 19

Project comparisons, in project analysis, 18; before and after method, 21; with or without method, 21

Retorts, charcoal, 127

Resource assessment, 5; fuel, 7–8; steps, 37–38; technology, 5, 12

Resource management, 16

Resources. *See* Charcoal resources; Crop residue resources; Crop resources; Forest residues; Forest resources, nonsustainable; Forest resources, sustainable; Hydro resources; Solar resources; Wastes, animal or solid; Wind resources

Risk, 34

Run of the river systems. *See* Hydro technology, intake systems

Second Law of Thermodynamics, 13. *See also* Net energy efficiency

Selection criteria. *See* Decision criteria, in project analysis

Shadow pricing, 29

Shadow values, 23

Simple payback period, 33

Site verification, for wind resources, 114–15

Social accounts, 20, 21

Social opportunity cost. *See* Shadow values

Social values, as part of economic analysis, 24. *See also* Shadow pricing

Solar resources: data sources, 91–94; definitions, 85–86; equations, 89–91; measurement methods, 86–91; planning, 94; uses, 84–85

Solar technology, 148–50; air conditioning, 159–60; applications, 151; conversion efficiencies, 152, 156, 159; definitions, 150; desalination, 160; economics, 160; equations, 155–57; example, 157–58, 160–62; lighting systems, 158–59; photovoltaic systems, 149, 150, 154–55; potential, 148; thermal systems, 149–50, 151–54; water heating, 152–54; water pumping, 159–60

Storage ponds. *See* Hydro technology, intake systems

Stove technology: conversion efficiencies, 121–24; data, 123–24; economics, 124–26; efficiency tests, 118–19; efficiency versus fuel economy, 123; equations, 121; example, 121–23; measurement problems, 118; mud versus metal, 122–23

Time horizon, 18, 21, 22

Time value of money, 25–27

Two-tiered tariff, 192

Uncertainty, 34

Usable energy. *See* Energy, usable

Valuation measures, in project analysis, 18, 19, 23–31

Wastes, animal or solid, 76–77; data, 79; definitions, 78; equation, 77; example, 79; production, 208–9

Water boiling test. *See* Stove technology: efficiency tests

Water resources. *See* Hydro resources

Weighted valuation, 24

Weights, in economic analysis, 25

Wind resources, 106; data, 109–15; definitions, 107–8; equations, 108; evaluation, 112–15; information sources, 109–10, 112

Wind technology: annual energy, 180; choosing a machine, 181–84; conversion efficiencies, 179; data, 179; definitions, 175–78; equations, 175, 176, 179, 180; example, 184–87; overall power coefficient, 179; power source, 178–79; site selection, 181

With or without method. *See* Project comparisons

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