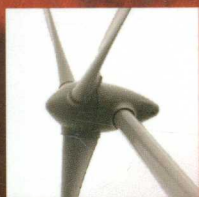# BENT SØRENSEN

RENEWABLE

ENERGY
CONVERSION, TRANSMISSION AND STORAGE

Renewable Energy Conversion, Transmission and Storage

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Other books by the author:

Hydrogen and Fuel Cells. 2005
Renewable Energy, 3rd ed. 2004
Life-cycle analysis of energy systems (with Kuemmel and Nielsen). 1997
Blegdamsvej 17. 1989
Superstrenge. 1987
Fred og frihed. 1985
Fundamentals of Energy Storage (with Jensen). 1984
Energi for fremtiden (with Hvelplund, Illum, Jensen, Meyer and Nørgård). 1983
Energikriser og Udviklingsperspektiver (with Danielsen). 1983
Renewable Energy. First edition, 1979; Second edition 2000
Skitse til alternativ energiplan for Danmark (with Blegaa, Hvelplund, Jensen, Josephsen, Linderoth, Meyer and Balling). 1976

More information about the author at http://energy.ruc.dk

Preface

It is increasingly becoming accepted that renewable energy has a decisive place in the future energy system and that the "future" may not be very far away, considering not just issues of greenhouse gas emissions and the finiteness of fossil and nuclear resources, but also their uneven distribution over the Earth and the increasing political instability of precisely those regions most endowed with the remaining non-renewable resources.

Renewable energy sources have been the backbone of our energy system during most of human history, interrupted by a brief interval of cheap fuels that could be used for a few hundred years in a highly unsustainable way. Unfortunately, this interval has also weakened our sensibility over wasteful uses of energy. For a long time, energy was so cheap that most people did not think it worthwhile to improve the efficiency of energy use, even if there was money to save. Recent analysis has shown that a number of efficiency improvements that would use already existing technology could have been introduced at a cost lower than that of the energy saved, even at the prevailing low prices. We now know that any renewal of our energy supply-system would probably be more (although not necessarily a lot more) expensive than the present cost of energy, and although this book is about the prospects for filling our future energy needs with a range of renewable technologies, it must still be emphasised that carrying though all efficiency improvements in our conversion system, that can be made at lower cost than the new system, should be done first, and thereby buying us more time to make the supply transition unfold smoothly.

This book is based on the energy conversion, transmission and storage parts of the author's *Renewable Energy*, the book that in 1979 placed the topic on the academic agenda and actually got the term "renewable energy" accepted. While *Renewable Energy* (now in its third edition) deals with the physical, technical, social, economic and environmental aspects of renewable energy, the present book concentrates on the engineering aspects, in order to provide a suitable textbook for the many engineering courses in renewable energy coming on-line, and hopefully at the same time providing a handy primer for people working in this important field.

Gilleleje, June 2007, *Bent Sørensen*

Units and conversion factors

Powers of 10[□]

Prefix	Symbol	Value	Prefix	Symbol	Value
atto	a	10^{-18}	kilo	k	10^3
femto	f	10^{-15}	mega	M	10^6
pico	p	10^{-12}	giga	G	10^9
nano	n	10^{-9}	tera	T	10^{12}
micro	μ	10^{-6}	peta	P	10^{15}
milli	m	10^{-3}	exa	E	10^{18}

SI units

Basic unit	Name	Symbol
length	metre	m
mass	kilogram	kg
time	second	s
electric current	ampere	A
temperature	Kelvin	K
luminous intensity	candela	cd
plane angle	radian	rad
solid angle	steradian	sr
amount[#]	mole	mol

Derived unit	Name	Symbol	Definition
energy	joule	J	$kg\ m^2\ s^{-2}$
power	watt	W	$J\ s^{-1}$
force	newton	N	$J\ m^{-1}$
electric charge	coulomb	C	$A\ s$
potential difference	volt	V	$J\ A^{-1}\ s^{-1}$
pressure	pascal	Pa	$N\ m^{-2}$
electric resistance	ohm	Ω	$V\ A^{-1}$
electric capacitance	farad	F	$A\ s\ V^{-1}$
magnetic flux	weber	Wb	$V\ s$
inductance	henry	H	$V\ s\ A^{-1}$
magnetic flux density	tesla	T	$V\ s\ m^{-2}$
luminous flux	lumen	lm	$cd\ sr$
illumination	lux	lx	$cd\ sr\ m^{-2}$
frequency	hertz	Hz	$cycle\ s^{-1}$

[□] G, T, P, E are called milliard, billion, billiard, trillion in Europe, but billion, trillion, quadrillion, quintillion in the USA. M as million is universal.
[#] The amount containing as many particles as there are atoms in 0.012 kg ^{12}C.

Conversion factors

Type	Name	Symbol	Approximate value
energy	electon volt	eV	1.6021×10^{-19} J
energy	erg	erg	10^{-7} J (exact)
energy	calorie (thermochemical)	cal	4.184 J
energy	British thermal unit	Btu	1055.06 J
energy	Q	Q	10^{18} Btu (exact)
energy	quad	q	10^{15} Btu (exact)
energy	tons oil equivalent	toe	4.19×10^{10} J
energy	barrels oil equivalent	bbl	5.74×10^{9} J
energy	tons coal equivalent	tce	2.93×10^{10} J
energy	m^3 of natural gas		3.4×10^{7} J
energy	kg of methane		6.13×10^{7} J
energy	m^3 of biogas		2.3×10^{7} J
energy	litre of gasoline		3.29×10^{7} J
energy	kg of gasoline		4.38×10^{7} J
energy	litre of diesel oil		3.59×10^{7} J
energy	kg of diesel oil/gasoil		4.27×10^{7} J
energy	m^3 of hydrogen at 1 atm		1.0×10^{7} J
energy	kg of hydrogen		1.2×10^{8} J
energy	kilowatt hour	kWh	3.6×10^{6} J
power	horsepower	hp	745.7 W
power	kWh per year	kWh/y	0.114 W
radioactivity	curie	Ci	3.7×10^{8} s^{-1}
radioactivity	becqerel	Bq	1 s^{-1}
radiation dose	rad	rad	10^{-2} J kg^{-1}
radiation dose	gray	Gy	J kg^{-1}
dose equivalent	rem	rem	10^{-2} J kg^{-1}
dose equivalent	sievert	Sv	J kg^{-1}
temperature	degree Celsius	°C	K – 273.15
temperature	degree Fahrenheit	°F	9/5 C+ 32
time	minute	min	60 s (exact)
time	hour	h	3600 s (exact)
time	year	y	8760 h

UNITS AND CONVERSION FACTORS

| Type	Name	Symbol	Approximate value
pressure	atmosphere	atm	1.013×10^5 Pa
pressure	bar	bar	10^5 Pa
pressure	pounds per square inch	psi	6890 Pa
mass	ton (metric)	t	10^3 kg
mass	pound	lb	0.4536 kg
mass	ounce	oz	0.02835 kg
length	Ångström	Å	10^{-10} m
length	inch	in	0.0254 m
length	foot	ft	0.3048 m
length	mile (statute)	mi	1609 m
volume	litre	l	10^{-3} m^3
volume	gallon (US)		3.785×10^{-3} m^3

Contents

CONTENTS

INTRODUCTION

The structure of this book is to start with general principles of energy conversion and then move on to more specific types of conversion suitable for different classes of renewable energy such as wind, hydro and wave energy, solar radiation used for heat or power generation, secondary conversions in fuel cell or battery operation, and a range of conversions related to biomass, from traditional combustion to advanced ways of producing liquid or gaseous biofuels.

Because some of the renewable energy sources are fundamentally intermittent, and sometimes beyond what can be remedied by regional trade of energy (counting on the variability being different in different geographical regimes), energy storage must also be treated as an important partner to many renewable energy systems. This is done in the final chapters, after a discussion of transmission or transport of the forms of energy available in a renewable energy system. In total, the book constitutes an introduction to all the technical issues to consider in designing renewable energy systems. The complementary issues of economy, environmental impacts and planning procedures, as well as a basic physical-astronomical explanation of where the renewable energy sources come from and how they are distributed, may be found in the bulkier treatise of Sørensen (2004).

If used for energy courses, the teacher may find the "mini-projects and exercises" attached at the end useful. They comprise simple problems but in most cases can be used as mini-projects, which are issues discussed by individual students or groups of students for a period of one to a couple of weeks, and completed by submission of a project report of some 5-25 pages for evaluation and grading. These mini-projects may involve small computer models made by the students for getting quantitative results to the problems posed.

General principles do not wear with time, and the reference list contains many quite old references, reflecting a preference for quoting those who first discussed a given issue rather than the most recent marginal improvement.
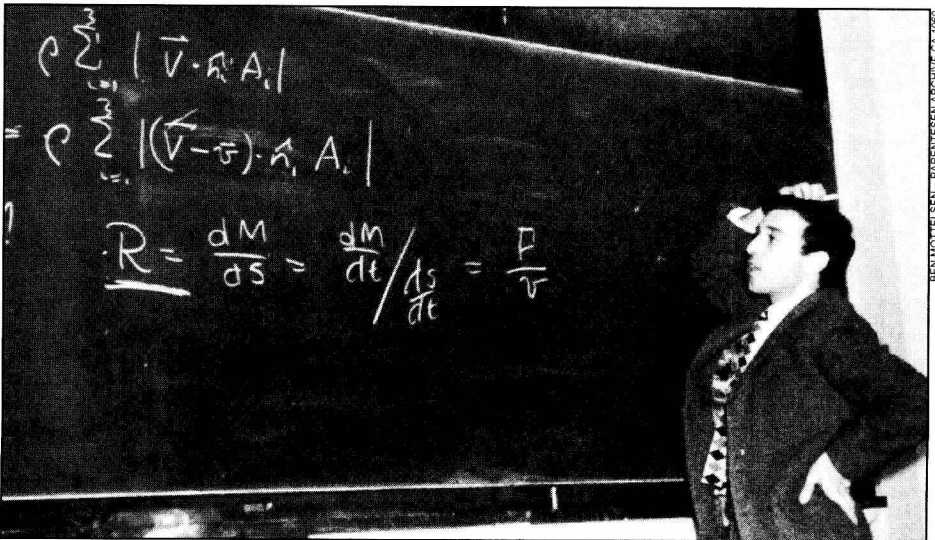
I. GENERAL PRINCIPLES

BASIC PRINCIPLES OF ENERGY CONVERSION

A large number of energy conversion processes take place in nature. Man is capable of performing a number of additional energy conversion processes by means of various devices invented during the history of man. Such devices may be classified according to the type of construction used, according to the underlying physical or chemical principle, or according to the forms of energy appearing before and after the action of the device. In this chapter, a survey of conversion methods, which may be suitable for the conversion of renewable energy flows or stored energy, will be given. A discussion of general conversion principles will be made below, followed by an outline of engineering design details for specific energy conversion devices, ordered according to the energy form being converted and the energy form obtained. The collection is necessarily incomplete and involves judgment about the importance of various devices.

2.1 Conversion between energy forms

For a number of energy forms, Table 2.1 lists some examples of energy conversion processes or devices currently in use or contemplated, organised according to the energy form emerging after the conversion. In several cases more than one energy form will emerge as a result of the action of the device, e.g. heat in addition to one of the other energy forms listed. Many devices also perform a number of energy conversion steps, rather than the single ones given in the table. A power plant, for example, may perform the conversion process chain between energy forms: chemical → heat → mechanical → electrical. Diagonal transformations are also possible, such as conversion of mechanical energy into mechanical energy (potential energy of elevated fluid → kinetic energy of flowing fluid → rotational energy of

turbine) or of heat into heat at a lower temperature (convection, conduction). The second law of thermodynamics forbids a process in which the only change is that heat is transferred from a lower to a higher temperature. Such transfer can be established if at the same time some high-quality energy is degraded, e.g. by a heat pump (which is listed as a converter of electrical into heat energy in Table 2.1, but is discussed further in Chapter 6).

Initial ener-gy form	Converted energy form				
	Chemical	*Radiant*	*Electrical*	*Mechanical*	*Heat*
Nuclear					Reactor
Chemical			Fuel cell, battery dis-charge		Burner, boiler
Radiant	Photolysis		Photovoltaic cell		Absorber
Electrical	Electrolysis, battery charg-ing	Lamp, laser		Electric motor	Resistance, heat pump
Mechanical			Electric gen-erator, MHD	Turbines	Friction, churning
Heat			Thermionic & thermoelectric generators	Thermody-namic en-gines	Convector, radiator, heat pipe

Table 2.1. Examples of energy conversion processes listed according to the initial energy form and one particular converted energy form (the one primarily wanted).

The efficiency with which a given conversion process can be carried out, i.e. the ratio between the output of the desired energy form and the energy input, depends on the physical and chemical laws governing the process. For the heat engines, which convert heat into work or vice versa, the description of thermodynamic theory may be used in order to avoid the complication of a microscopic description on the molecular level (which is, of course, possible, e.g. on the basis of statistical assumptions). According to thermodynamic theory (again the "second law"), no heat engine can have an efficiency higher than that of a reversible Carnot process, which is depicted in Fig. 2.1, in terms of different sets of thermodynamic state variables,

(P, V) = (pressure, volume),
(T, S) = (absolute temperature, entropy),

and

(H, S) = (enthalpy, entropy).

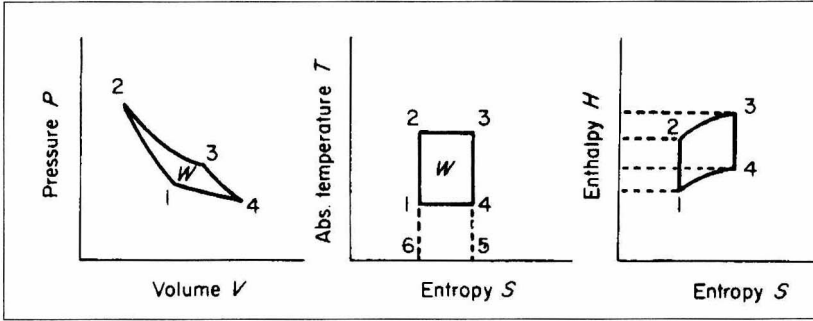*Figure 2.1.* The cyclic Carnot process in different representations. Traversing the cycle in the direction $1 \to 2 \to 3 \to 4$ leads to the conversion of a certain amount of heat into work (see text for details).

The change of the entropy S during a process (e.g. an energy conversion process), which brings the system from a state 1 to a state 2, is defined by

$$\Delta S = \int_{T_1}^{T_2} T^{-1} \, dQ, \tag{2.1}$$

where the integral is over successive infinitesimal and reversible process steps (not necessarily related to the real process, which may not be reversible), during which an amount of heat dQ is transferred from a reservoir of temperature T to the system. The imagined reservoirs may not exist in the real process, but the initial and final states of the system must have well-defined temperatures T_1 and T_2 in order for (2.1) to be applicable. The entropy may contain an arbitrary common constant fixed by the third law of thermodynamics (Nernst's law), which states that S may be taken as zero at zero absolute temperature ($T = 0$).

The enthalpy H is defined by

$$H = U + PV,$$

in terms of P, V and the internal energy U of the system. According to the first law of thermodynamics, U is a state variable given by

$$\Delta U = \int dQ + \int dW, \tag{2.2}$$

in terms of the amounts of heat and work added to the system [Q and W are not state variables, and the individual integrals in (2.2) depend on the paths of integration]. The equation (2.2) determines U up to an arbitrary constant, the zero point of the energy scale. Using the definition (2.1),

$$dQ = T \, dS$$

and

$$dW = -P\,dV,$$

both of which are valid only for reversible processes The following relations are found among the differentials:

$$dU = T\,dS - P\,dV,$$
$$dH = T\,dS + V\,dP. \tag{2.3}$$

These relations are often assumed to have general validity.

If chemical reactions occur in the system, additional terms $\mu_i\,dn_i$ should be added on the right-hand side of both relations (2.3), in terms of the chemical potentials μ_i (see e.g. Maron and Prutton, 1959).

For a cyclic process such as the one shown in Fig. 2.1, $\int dU = 0$ upon returning to the initial locus in one of the diagrams, and thus according to (2.3) $\int T\,dS = \int P\,dV$. This means that the area enclosed by the path of the cyclic process in either the (P, V) or the (T, S) diagram equals the work $-W$ performed by the system during one cycle (in the direction of increasing numbers on Fig. 2.1).

The amount of heat added to the system during the isothermal process 2-3 is $\Delta Q_{23} = T(S_3 - S_2)$, if the constant temperature is denoted T. The heat added in the other isothermal process, 4-1, at a temperature T_{ref} is $\Delta Q_{41} = -T_{ref}(S_3 - S_2)$. It follows from the (T, S) diagram that $\Delta Q_{23} + \Delta Q_{41} = -W$. The efficiency by which the Carnot process converts heat available at temperature T into work, when a reference temperature of T_{ref} is available, is then

$$\eta = \frac{-W}{\Delta Q_{23}} = \frac{T - T_{ref}}{T}. \tag{2.4}$$

The Carnot cycle (Fig. 2.1) consists of four steps: 1-2, adiabatic compression (no heat exchange with the surroundings, i.e. $dQ = 0$ and $dS = 0$); 2-3, heat drawn reversibly from the surroundings at constant temperature (the amount of heat transfer ΔQ_{23} is given by the area enclosed by the path 2-3-5-6-2 in the (T, S)-diagram); 3-4, adiabatic expansion; and 4-1, heat given away to the surroundings by a reversible process at constant temperature [$|\Delta Q_{41}|$ equal to the area of the path 4-5-6-1-4 in the (T, S)-diagram].

The (H, S)-diagram is an example of a representation in which energy differences can be read directly on the ordinate, rather than being represented by an area.

It requires long periods of time to perform the steps involved in the Carnot cycle in a way that approaches reversibility. As time is important for man (the goal of the energy conversion process being power rather than just an amount of energy), irreversible processes are deliberately introduced into