

**ENVIRONMENTAL ENERGY FLOWS
IN THE NEW ZEALAND
ECONOMIC SYSTEM**

by

J. T. Baines and D. J. Smith

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SUMMARY

An understanding of the energy basis for human societies is incomplete if the current and recent energy flows in the global system are not recognised. These contributions include sunlight, wind, rain, ocean waves and tides.

If, as we believe, mankind's long term future is constrained by the limits imposed by sustainable energy supplies, then we must acknowledge the relationship that exists between socio-economic systems and their supporting environmental systems.

For a long time people have recognised that the sun is an important source of energy supporting economic activity. However, some points of view have been advanced recently which discount the need to evaluate environmental energy flows and to include such evaluations in planning. Some argue that energy flows derived from current and recent solar energy inputs to the global system are beyond the sphere of interest of economic analysis since they do not have a money value. Such flows are beyond man's direct influence and the economic system regards them as "free goods". Others assert that such flows are so large that their inclusion in calculations dwarfs all other energy sources.

Much has been done recently to assess the validity of these arguments and to overcome the theoretical and practical problems in such energy analyses. Analysis based on the concept of Embodied energy now enables the assembly and interpretation of previously disjointed information to provide a more holistic view of the world in which we live.

This paper is a first attempt to rationalise and extend energy analyses of the systems of New Zealand by including environmental energy flows. The major flows are evaluated as annual averages and the relative utilities of the various flows are assessed in terms of their Energy Transformation Ratios.

The calculations provide preliminary estimates only and are described in detail to enable others to improve upon them later as better information and clearer perceptions evolve.

ENVIRONMENTAL ENERGY FLOWS

IN THE NEW ZEALAND ECONOMIC SYSTEM

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December 1982

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Table of Contents

	Page
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INTRODUCTION	5

Energy sources for mankind	5
Flows and Transformations of energy	6
Energetic and Economic systems	7
Thermodynamic relationships	8
Embodied energy	11
Energetic evaluation	13
Energy chains and webs and Energy Quality	13
Energetic accounting and units	16
Energy numeraire	16
Energy transformation ratios	17
Mankind's uses of energy	20
National energy signatures	20
METHODOLOGY	21

(1) Distribution of solar energy absorbed by the earth-atmosphere system according to the major sunlight-harnessing interactions.	22
Table 1.	22
Footnotes to Table 1.	25
(2) Redistribution of absorbed solar energy via the major global environmental energy fluxes.	28
Table 2.	29
Footnotes to Table 2.	29
(3) "First law" estimates of the major environ- mental energy fluxes flowing into New Zealand	36
Table 3.	36
Footnotes to Table 3.	36
(4) Annual environmental energy inputs to the New Zealand system.	40
Table 4.	41
Footnotes to Table 4.	41
REFERENCES	47

APPENDIX I

Global disposition of the mean annual solar radiation intercepted at the surface of the earth's atmosphere.

49

APPENDIX II

Summary of energy symbols used in the diagrams.

51

INTRODUCTION

Energy Sources for Mankind.

During the twentieth century it has seemed that fossil fuels are the most important primary sources of energy used by the earth's human population. This is true in the sense that fossil fuels are amongst the highest quality sources of primary energy supporting man's economic activities. They are concentrated in forms that mankind has learned to use effectively and they have been readily accessible. Indeed, the availability of fossil fuels has been largely responsible for the industrialisation of many human societies at rates that would have been inconceivable otherwise.

However, mankind depends not only on social and economic structures. Human populations are just as surely supported by the earth's natural systems - rivers, forests, native bushlands, fish-bearing coastal shallows, grasslands and so on. These natural systems do not depend upon the availability of fossil fuels for their maintenance and growth. On the other hand, the functioning of such natural systems can be influenced by fossil fuel-based activities, mediated by mankind. Their principal energy source is sunlight, supplemented by small amounts of thermal energy from the earth's interior and tidal energy from the gravitational interactions between the earth, the moon and the sun.

Only a small fraction of the matter at the earth's surface exists in the form of living organisms. Plants capture incident solar radiation (and store it as the chemical energy of biomass) by the mechanism of photosynthesis. The process of photosynthesis/respiration results from the interaction of many flows - carbon dioxide; water; soil nutrients such as phosphorus, nitrogen, magnesium, calcium; and environmental heat.

These flows are themselves driven by the flux of incoming solar energy. Solar-driven winds distribute gases; the solar-driven hydrologic cycle distributes water around the globe; the partially solar-driven geo-mechanical cycle contributes to the land's physical structure through the process of uplift.

In this paper we discuss the evaluation of some of the major environmental energy fluxes in the global system and for New Zealand.

Flows and Transformations of Energy.

Throughout our earth-atmosphere system energy is constantly flowing. In one form or another, it flows spontaneously whenever some spatial potential gradient exists.

Energy enters our earth-atmosphere system continuously from its solar source at 6000 K. This flow is relatively high-frequency electromagnetic radiation with a modal wavelength of 0.5 micron. When this flow impinges on matter, the energy is immediately transformed. That which is absorbed, excites the molecules of the absorbing material and can give rise to several sorts of change:-

- * a gas will heat up, expand and flow along a temperature/density gradient in order to equilibrate;

- * a liquid will heat up, may expand a little and flow along a temperature gradient in order to equilibrate;

- * a solid will heat up, may expand and will begin emitting electromagnetic radiation at a higher frequency than before (although at a much lower frequency than the incoming radiation) in order to restore the energetic equilibrium;

- * some photosensitive materials will undergo a change in their chemical composition or structure as a result of this energy input. The products of such light-driven processes will be chemical species that are at higher levels of stored chemical potential energy (Gibbs Free Energy levels) than the initial reactants which received the sunlight.

Part of the incoming solar radiation is not absorbed immediately but is reflected at the same frequency as before though now in a diffuse pattern. Some of this will subsequently be absorbed elsewhere in the earth-atmosphere system whilst some simply reflects out into the solar system again.

From an initially uniform energy flow with no material dimension (as it passes through the vacuum which separates earth from sun), it enters the earth-atmosphere system, interacts with matter and is transformed into a myriad different energy flows, all associated with storages or flows of matter. Such transformations continue throughout the earth-atmosphere system. They are manifest in the

numerous physical and chemical cycles that comprise our global system's metabolism.

One inevitable product of any metabolic process is the emission of low-temperature heat. The thermal equilibrium of the global system is ultimately maintained by the outward flow of terrestrial radiation, a relatively low frequency electromagnetic radiation with modal wavelength of 10 microns.

In terms of calorific content, the inward and outward flows of radiation are balanced. In terms of their thermodynamic potential to do work, the terrestrial radiation is of far lower value, characterised by a much lower source temperature - about 285 K. The solar radiation, in driving the global transformation processes has transferred its high thermodynamic potential to the principal products of those transformation processes - the physical natural and man-made systems of the earth.

Energetic and Economic Systems.

Economic systems are defined by the extent of human economic activity in prescribed geographical regions. Such economic systems are subsystems of the (spacially) larger ecologic systems.

It is clear that mankind depends on energy supplies from the sun. What fossil fuels do is provide humans with highly concentrated energy forms that can act as accelerators or amplifiers. They assist in increasing yields from natural production systems; they allow us to create more energy-intensive processes and to move more rapidly from place to place; they provide synthetic material substitutes and give portability to energy supply. Fossil fuels are extremely useful. They are not essential, however, to mankind's survival (although they are definitely essential to the preservation of many of the urban and industrialised socio-economic structures of today).

Current methods for evaluating the whole range of goods and services that exist in our world are based exclusively on assessing the activities of people. In doing this, economics fails to acknowledge the fundamental role of the Sun. This state of affairs has probably come about as a result of the dominant position occupied by fossil fuels in the general awareness of energy matters. By and large, the USE of fossil fuels as we know it was introduced to the global ecologic-economic system by human activity. There is another important distinction between solar energy flows and fossil fuels and electricity which reinforces this explanation. Solar energy flows are not directly tradeable commodities but fossil fuels and electricity are.

Generally speaking, natural resources have no concomitant monetary value until some human services are involved in accessing them with a view to possible processing and utilisation within the formal economy. Although terms exist in economic theory such as "severance payments" and "economic rents on stock resources", there is little evidence of their practical application.

In order to understand the energy basis of global and local systems it is essential to be able to consider all energy sources. Since the continuous energy input from the sun accounts for 99.98% of the total steady-state energy supply to the earth (Hubbert), it is important to be able to include it quantitatively.

All goods and services in our ecological and socio-economic systems have a solar component of embodied energy. Without recognising the solar component, our understanding is incomplete.

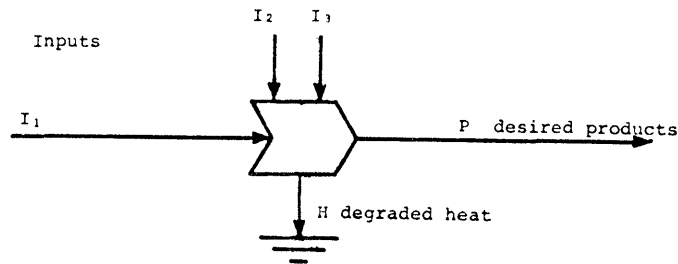
The calculations contained in this paper represent a first attempt by its authors to evaluate the environmental inputs to a socio-economic system - the New Zealand system. Better understanding of the complexities of our global ecological system and the application of more sophisticated methods of analysis will no doubt help to refine these numerical estimates. Nevertheless, in their present form, they provide a basis for further work.

Thermodynamic Relationships.

All energetic transformations are subject to what are believed to be inviolable physical constraints. These constraints are defined by the Laws of Thermodynamics. They apply equally to spontaneous, naturally occurring processes and to man-mediated processes. The Laws of Thermodynamics express several very important principles concerning Conservation, Spontaneity, and Irreversibility in energetic transformations.

Using the following symbolic notation to describe a generalised work process

Figure 1.



the 1st law says that energy is conserved i.e. $I_1 + I_2 + I_3 = P + H$. The 2nd law says that for any real world process there must be a flow, H , of energy that is degraded in the process (i.e. reduced in its potential to do useful work within the system).

Having summarised the 1st and 2nd laws, it is pertinent to clarify some important implications that derive from them. The 1st law of thermodynamics makes no distinction between energy types on the basis of work potential. The energy that flows through any transformation process or through any system is always conserved. This is so whether it is evaluated as calorific content or embodied energy content or some other designated energy attribute.

By itself, the 1st law makes no distinction between the different qualities or utilities of various energy forms. The differentiation between energy forms is described in the 2nd law. It is described in forms traditionally chosen by thermodynamicists - heat and mechanical work.

Mechanical work can be transformed into any other kind of energy form. All forms of energy can be transformed totally into heat but the reverse is impossible - heat cannot be converted totally into mechanical work (in real world processes at finite rates).

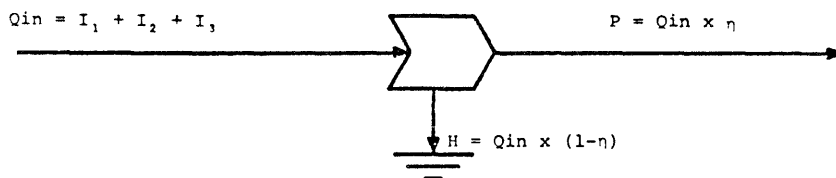
By the conventions of thermodynamics, heat and mechanical work represent the extremes of energy quality. Heat (with quality dependent on temperature) defines low

quality energy and mechanical work defines the high quality energy datum.

The calorific content method of energy evaluation (1st law evaluation) derives its traditional acceptability from this thermodynamic relationship between heat and mechanical work. However, because it uses the low quality extreme as the medium for comparison of energy forms and then assumes parity between calorific content and mechanical work forms of energy, it is now thought to be an inappropriate medium of comparison.

1st law evaluation of energy flows through transformations reduces all the energy flows to their lowest common denominator - heat equivalents, as measured in calorific content.

Figure 2.



In terms of calorific content, the division between flows "P" and "H" depends on the nature of the transformation. By definition, if a greater amount of the calorific content of the inputs ends up as heat at a thermodynamically lower potential than the inputs (i.e. if $\eta < 0.5$) then a lesser amount will reside in the desired product. Thus comparison of energy forms (in this case $q(\text{out})$ and $q(\text{h})$) on the basis of calorific content in some circumstances attaches more importance to the necessary by-product, degraded heat, than to the desired product of the transformation. Clearly, evaluation by calorific content may contradict evaluation by embodied energy content.

In assessing the usefulness of any embodied energy form, heat release from a process (work process or combustion process etc.) is considered an irrelevant criterion for comparison since:-

(1) it ignores the important aspect of actual end use, without which an energetic evaluation is meaningless;

(2) it gives no recognition to the embodied energy content of the energy sources involved in the process; and

(3) it ignores any consideration of Time.

Furthermore, heat flow from a combustion process is almost invariably only an intermediate product in any energy transformation. Petrol is burned in a motorcar to provide locomotion; food is eaten by animals to build and maintain bodily structure and to drive the processes of the controlling nervous system; chlorophyll uses sunlight in order to synthesise carbohydrates; and so on. In all these processes, heat MUST be dissipated and therefore it flows - but it is not the prime reason for the event. The level of this heat flow can hardly be considered a sound criterion by which the system should evaluate the process or the products since the extent of this dissipating heat flow is not necessarily characteristic of the transformation process occurring.

2nd law evaluations measure energy availabilities with reference to the two extreme states - heat and mechanical work. They are based on the assumption that mechanical work is an appropriate reference quality for energy.

Embodied Energy.

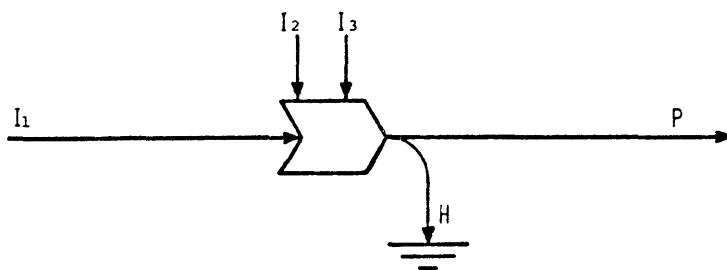
Not being confined only to processes that transform heat to mechanical work or vice versa, energy analysis requires a more generalised medium of comparison than that of calorific content - hence the use of embodied energy evaluations.

In an energetic interpretation of a work process, when two or more energy flows interact in a real process, the transformation that takes place is always characterised by a dual change: some of the interacting energy is upgraded at the expense of the remainder, which is downgraded (in its ability to do useful work within the system). The upgraded energy appears as the desired product of the transformation. Downgraded energy inevitably appears in the form of heat released to the surroundings. In effect, desired output P

and degraded heat H are essential co-products of any real energy transformation process.

Thus the symbolic diagram given above could be redrawn in the following manner:-

Figure 3.



Since P could not exist without H , embodied energy evaluations account for H as a necessary requirement in the production of P . Thus P is evaluated numerically as the summation of the embodied energies of I_1 , I_2 and I_3 .

This convention, while complying explicitly with both laws of thermodynamics, still is subject to the arbitrary definition of what is desired product. The flow H is not designated a desired product although it is an essential co-product. The distinction between P and H depends therefore on human perceptions of usefulness. It follows from this that the numerical evaluation of P depends on this distinction. **

Nevertheless, the present convention for embodied energy evaluation can be expressed as follows:

** Alternative methods for dealing with the evaluation of P and H could stem from treating it as a partitioning problem. In one case, a numerical estimate of $H(\min)$ could be subtracted from the embodied energy evaluation of P . In another case, it could be observed that we are dealing with RELATIVE values anyway and thus the numerical value of $H(@T=288K)$ could be assigned as zero.

In an energetic transformation all the energy inputs are considered to be embodied in the desired product(s). By this definition, it is clear that all flows and storages have embodied energy, indicative of the total amount of energy that was sequestered in its production. For clarification, several examples are given below:-

* the flow of kinetic energy of wind embodies the energy of the sunlight that gave rise to temperature gradients on interaction with air and other thermal masses;

* the store of freshwater in inland lakes embodies the energy of the sunlight which evaporated and heated the resultant water vapour prior to its condensation into rain;

* refined petrol embodies the energies of the crude oil and of the goods and services used in the refinement processes (N.B. in turn, the crude oil embodies the energy of the sunlight which contributed to the biomass formation and its subsequent decay into the fossilised form - a process that took many thousands of years);

* a pencil embodies the energies that went into growing, harvesting and fashioning the wood and into concentrating, mining and forming the carbon "lead".

Energetic Evaluation.

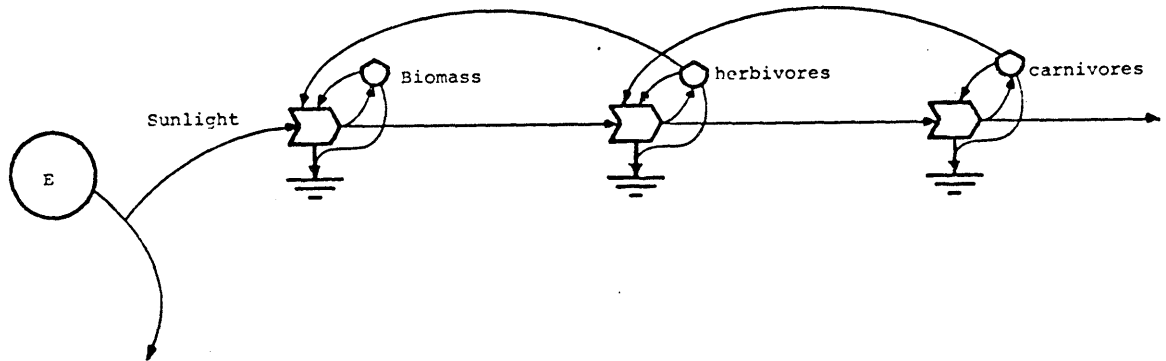
Evaluations reflect the dual influences of producers and consumers. In energetic terms, the producers value is the energy requirement of production - in other words, the embodied energy of the product. The consumers value is the energy effect derived from using the product. Optimal use (so far as the system as a whole is concerned) is achieved when the effect of using the product is well matched with the energy requirement of the product.

Embodied energy evaluations which take into account system-wide resource requirements and effects may be said to represent "the value to the system as a whole" of the product in energetic terms.

Energy Chains and Webs and Energy Quality.

Some energy forms are derived from virtually instantaneous transformations from sunlight, e.g. wind and rain; others are the end result of longer sequences of transformations, e.g. food chains.

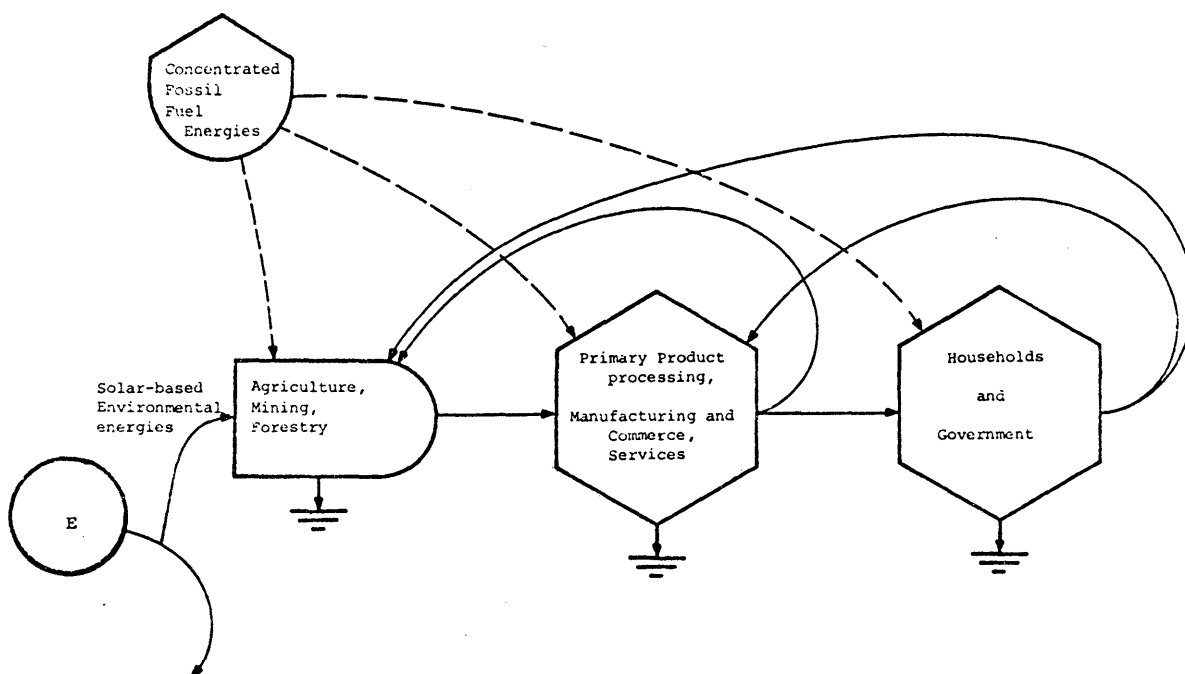
Figure 4.



In such a chain as this, sunlight is progressively concentrated through each successive transformation. At each step in the chain the desired output is of energetically higher quality (more embodied energy per unit).

A similar pattern exists in socio-economic systems.

Figure 5.



Most energetic chains involve controlling feedbacks - they are more accurately described as webs of interacting energy flows and storages. As solar energy flows through the web, the interconnecting transformations concentrate it into higher quality energy forms, e.g. sunlight -> wood -> paper -> information.

Systems of all kinds invest energy (feedbacks) in order to harness new energy inputs and thus create new embodied energy flows. The greater the perceived usefulness of the new embodied energy flow, the greater will be the system's "willingness" to invest energy to achieve this. This is a corollary to the principle stated above about "optimal use". Embodied energy evaluations may thus be seen to indicate the IN USE value to the system as a whole, assessed by current real patterns of usage.

Evaluation of energy transformation ratios (see subsequent section) enables the systematic assessment of different types of energy according to their Energy Quality. In these terms, higher energy quality implies that the system as a whole (usually defined by some appropriate physical boundary) has involved more of its energy supplies in the production of the given embodied energy type.

Energetic Accounting and Units.

Like financial accounting, energetic accounting embraces a variety of accounting tasks - identifying quantities; adding quantities of dissimilar materials or services; establishing value relativities amongst competing processes or products; and so on.

Economics has adopted the use of a "numeraire good", the unit of currency, for such accounting purposes. The practice enables economists and accountants to evaluate their variables with a uniform and universally accepted common measurement. This is done by expressing the value that society attaches to a unit of each good or service in terms of an associated currency value - hence \$/hr, \$/kg, c/litre, \$/cu.m., c./kWh, \$m/PJ.

The same need exists in energetic accounting procedures, since all energy forms are not of equal value to the system. As observed earlier, the calorific content of an energy flow is not an appropriate indicator of comparative usefulness. In energy accounting, it is the embodied energy associated with each unit that represents the value of each energy form to the system as a whole. This is so because the system as a whole has "invested" all that embodied energy in the production of the given energy form.

It is thus essential to be able to express embodied energy in terms of a single common denominator.

Energy Numeraire.

In this paper we have used the Solar Constant Joule as the energetic "numeraire". The Solar Constant Joule is defined as a unit of electromagnetic radiant energy assessed as it first reaches our earth-atmosphere system (i.e. at the outer surface of the atmosphere). As the flow of primary solar energy passes initially through the global ecological systems and subsequently through the numerous human socio-economic systems, it is transformed many times over and becomes embodied in all the goods and services that exist in the earth-atmosphere system. The units of this primary energy source therefore provide a useful "numeraire" in which to express the embodied energy evaluation of all goods and services - thus we have SCJ/J wind energy, SCJ/kg biomass, SCJ/bbl oil, SCJ/\$production, etc.

Other "numeraires" have been used. Early work of this kind used Fossil Fuel Equivalents (FFE); then Coal Equivalent Joules (CEJ) emerged as another step in refining the evaluation procedure; \$ equivalents are the most common numeraire good; even labour units have been postulated in

the past.

It should not be inferred that the Solar Constant Joule is the only one that should be used or even the best "numeraire" - it does however make for a scale of energy quality that begins at unity and increases. As with differing national monetary currencies, it should always be possible to convert easily from one "numeraire" to another, e.g. from Solar Constant Joules (SCJ) to Coal Equivalent Joules (CEJ).

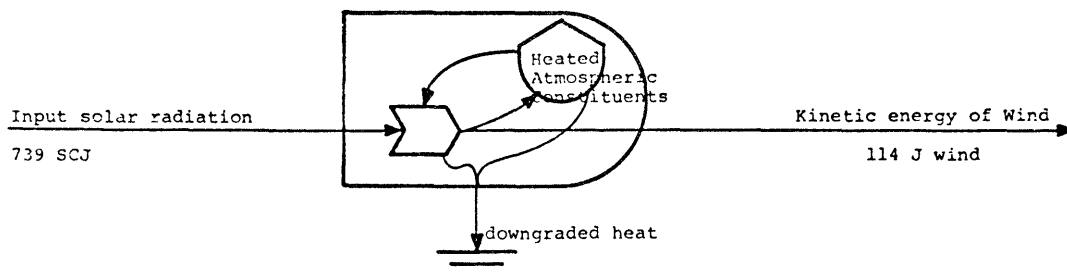
Energy Transformation Ratios.

When several flows of energy interact to cause a transformation, the sum total of the energy inputs is embodied in the outputs.

Energy Transformation Ratios are unique multiplicative factors which can be applied to each type of energy involved in the transformation. They are necessary to allow us to add together inputs to the process from sources of differing energy quality. This summation of energy inputs - in a single common energy unit - enables us to determine the Energy Transformation Ratio (sometimes called the Energy Quality Factor) for the desired output of the process in question. Several examples are given below:-

*1 energy transformation from incident solar radiation to the kinetic energy of wind:

Figure 6.



(See Footnote B, Table 2)

Energy input = input of solar radiation = 739 SCJ;

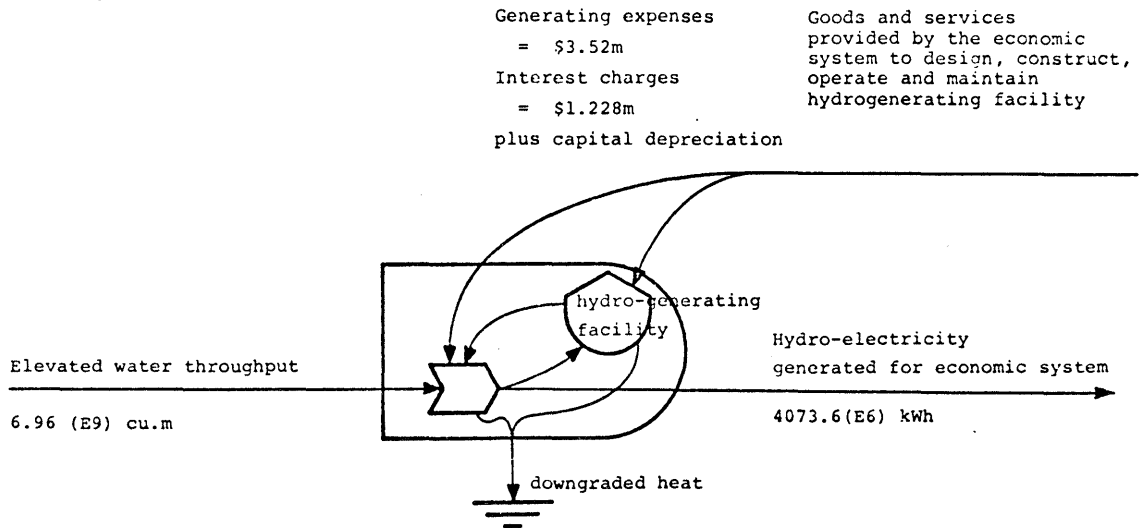
Energy output = kinetic energy of wind = 114 J wind;

Hence, Energy Transformation Ratio (ETR) for this transformation:

$$= \frac{739 \text{ SCJ}}{114 \text{ J wind}} = 6.48 \text{ SCJ/J wind}$$

*2 energy transformation from gravitational potential energy of elevated water to hydro-electricity as generated:

Figure 7.



(See Footnote E, Table 4)

Energy input = embodied energy of (i) the water passing through the turbines, (ii) goods and service feedbacks from the economic system, and (iii) depreciation of the generating structure. Embodied energy of elevated water = (6.96E9 cu.m)(1000 kg/cu.m)(3.9E6 SCJ/kg) = 27.144E18 SCJ; embodied energy of generating expenses and interest charges = \$4.740m (\$1978) @ 0.32E12 SCJ/\$1978 = 1.51E18 SCJ; by a similar procedure, embodied energy of capital depreciation = 3.92E18 SCJ.

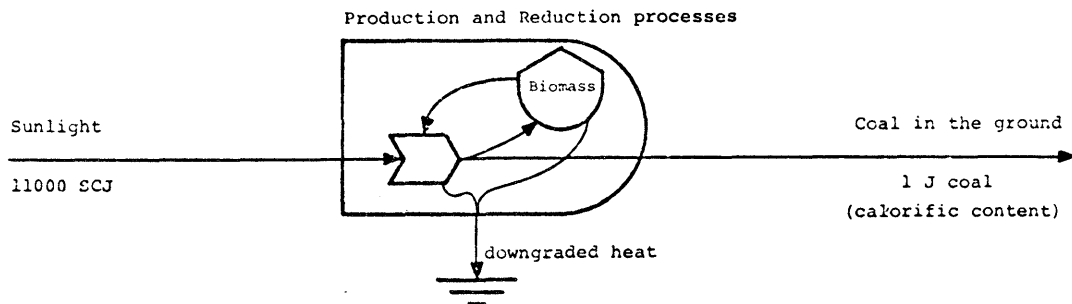
Energy output = electricity as generated = (4073.6E6 kWh)(3.6E6 J/kWh) = 14.665E15 J electricity.

Hence, ETR for this transformation:

$$= \frac{27144 + 5430}{14.665} = 2221 \text{ SCJ/J electricity}$$

*3 energy transformation from sunlight to the chemical potential energy stored in coal:

Figure 8.



(See Ref.14 - Odum et al.)

Energy input = sunlight = 11000 SCJ;

Energy output = coal deposit = 1 J coal (calorific value);

Hence, ETR for this transformation:

$$= \frac{11000}{1} = 11000 \text{ SCJ/J coal}$$

In effect, fossil fuels are the embodiment of many thousands of years of solar inputs to primary production and geo-mechanical conversion - they are stored solar energy from past eras.

The bulk of this paper is devoted to a series of calculations for deriving Energy Transformation Ratios for certain major environmental energy fluxes - the chemical and gravitational potential energies of elevated rainwater; the kinetic energies of winds and waves. This procedure is a

necessary step towards evaluating the total energy base for any system.

Mankind's Uses of Energy.

It is not possible to separate the primary energy sources according to the uses that people make of them. Solar and fossil energies contribute jointly to the production of all goods and services that are generated within socio-economic systems. The relative contributions of current solar and fossil energy sources vary according to the position in the global ecologic-economic web. In trees, the ratio of current solar to fossil energies is higher than it is in a weatherboard made from the wood of the tree.

It can be said that the relative proportions of current solar and fossil fuels supplied to an economic system will strongly influence the nature of the resulting structure. Countries with access to relatively large amounts of oil or coal invariably develop highly industrialised economies in contrast to those countries whose economies depend more heavily just on supplies of current solar energy.

The latter part of this paper contains calculations leading to estimates of the environmental energy inputs to New Zealand. These amount to New Zealand's total current solar energy supply.

National Energy Signatures.

Each separate country, even each separate geographical region within a country, will have its own unique environmental energy signature depending on its location on the earth's surface. Some countries have evolved more efficient systems for harnessing current solar energy than others; some countries are better endowed with natural mineral and fossil fuel reserves; all countries trade with others, i.e. exchange different forms of embodied energy.

A country or region's Energy Signature is simply a description of its unique combination of energy supplies. Each Energy Signature will give rise to a unique energetic structure as manifest in the natural ecologic and socio-economic systems of the region or country.

As a result, the same material or energy flow may have, in one country, an embodied energy value which is quite different from that in another country - e.g. electricity has a higher embodied energy value if it is predominantly coal- or oil-fired than if it is generated predominantly from hydro sources. The embodied energy of the downstream products of electricity will be similarly different, country by country.

METHODOLOGY

The method of evaluation evolved as follows:

(1) The total quantity and distribution of incoming solar radiation was estimated. The numerical values are summarised in Table 1.

(2) Global Energy Transformation Ratios for some environmental energy fluxes were estimated based on the data collected in Table 1. A summary of these results is presented in Table 2.

(3) The calorific equivalents ("first law" values) of the major environmental energy fluxes flowing into New Zealand were estimated. These results appear in Table 3.

(4) The total annual environmental energy input to the New Zealand system was estimated.

Accompanying each table is a series of footnotes providing a detailed description of the calculations and data sources.

(1)
 DISTRIBUTION OF SOLAR ENERGY
 ABSORBED BY THE EARTH ATMOSPHERE SYSTEM
 ACCORDING TO
 THE MAJOR SUNLIGHT-HARNESSING INTERACTIONS.

We have assumed that the solar energy absorbed by the earth-atmosphere system initially drives photochemical reaction processes and generates direct heating effects. The solar energy input to photochemical processes is further disaggregated into the two categories, biological photosynthesis and "other" photochemical reactions occurring mainly in the upper atmosphere. Direct heating processes are also separated according to liquid-gas phase changes in the Hydrologic cycle and transport-related fluxes.

TABLE 1

Description of flux	Mean annual energy of flux J (E21)	%	Foot-note

TOTALS:			

Solar energy incident on top of the atmosphere	5688	100	A
Solar energy absorbed by the earth-atmosphere system	3655	64	A

PHOTOCHEMICAL PROCESSES:			

Input to biological photosynthesis	5	0.1	C
Input to atmospheric photochemical processes	482	8.5	D

Input to photochemical reactions in the earth-atmosphere system	487	8.6	B

DIRECT HEATING PROCESSES:			

Input to all direct heating processes in the earth atmosphere system	3168	55.4	E

IN THE ATMOSPHERE:			

Input to clouds	151	2.7	A
Input to other atmospheric heating	340	6.0	F

Solar input to direct heating in the atmosphere	491	8.7	F

TABLE 1 (CONTINUED)

AT EARTH'S SURFACE:			

Solar input to direct heating at the earth's surface	2677	47.1	G

AT LAND SURFACE:			

Input to evaporation on land	312	5.5	I
Input to elevating water from land	8	0.1	J
Input to heating land	456	8.0	K

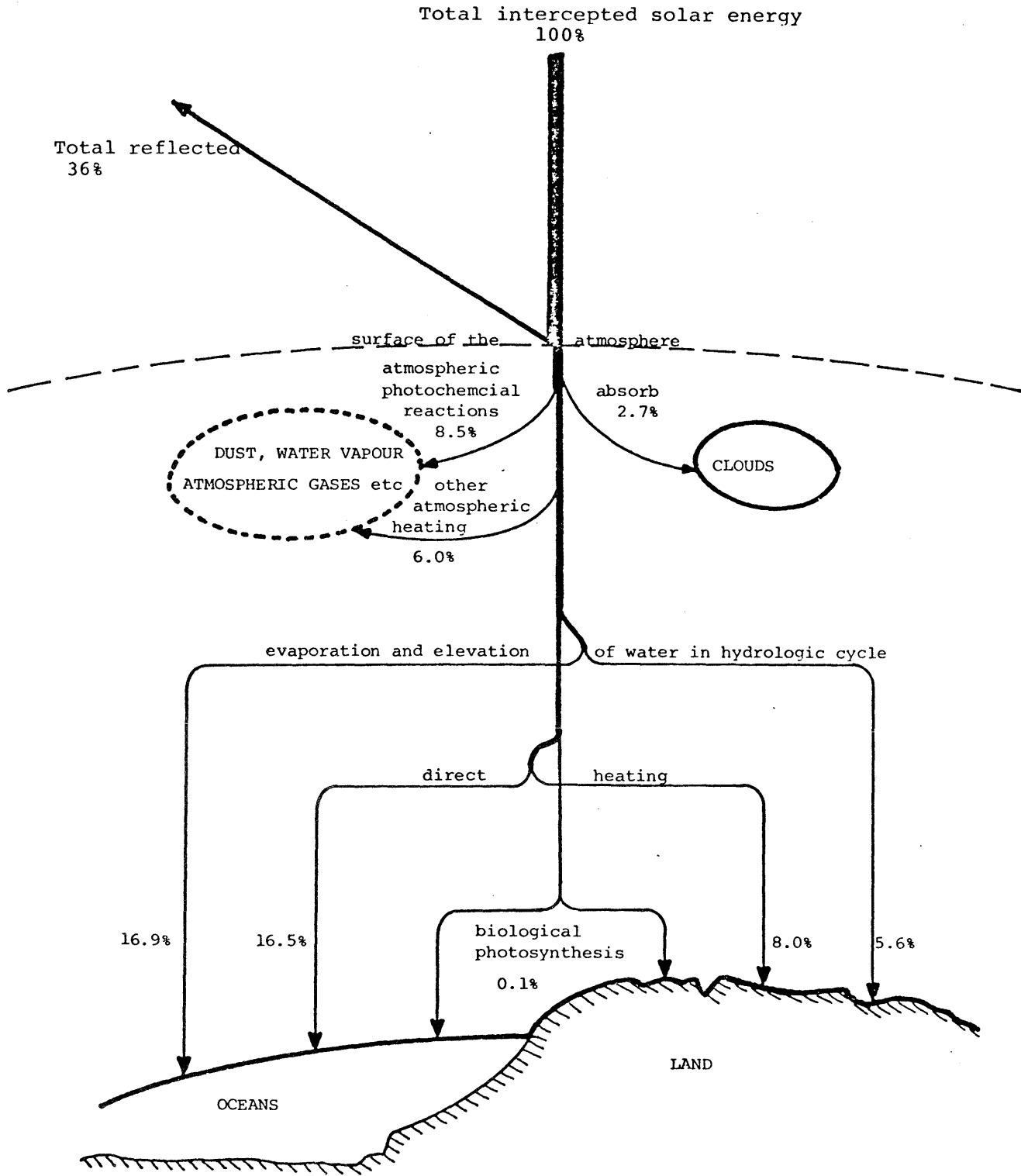
Solar input to direct heating at the land surface	776	13.6	H

AT OCEAN SURFACE:			

Input to evaporation from oceans	937	16.5	I
Input to elevating water from oceans	23	0.4	J
Input to heating oceans	941	16.5	K

Solar input to direct heating at the ocean surface	1901	33.4	H

Figure 9



Summary of major sunlight - harnessing interactions.

FOOTNOTES TO TABLE 1

A. From Appendix I. See also Sellers(1965) and Gustavson(1979).

B. Photochemical reactions involving (i) atmospheric gases and (ii) biological photosynthesis in oceans and on land.

C. Biological photosynthesis:

Kormondy(1969) p.18 provides an estimate of the average plant respiration as 30-40% of gross primary production, GPP - assumed 35% average. Erhlich et al(1977) p.74 estimated net primary production, NPP, at $96E12 \text{ W} = 3.02E21 \text{ J/yr}$.

$$\begin{aligned} \text{GPP} &= \text{NPP} \times (100/65) \\ &= 3.02(E21) \times (100/65) \\ \text{GPP} &= 4.7(E21) \text{ J/yr} \end{aligned}$$

D. Atmospheric photochemical reactions:

Erhlich et al.(1977) p.42 Ultra-violet radiation with wavelength <0.3 microns is all absorbed by oxygen and nitrogen above 50 km; and p.39 Fig 2-11 radiation intensity as a function of wavelength yields an estimate of solar energy in this wavelength range of 0.006 W/sq.cm . Area of the earth's surface = $5.1(E14) \text{ sq.m}$ (Times Atlas,1974) .

Hence solar energy absorbed by atmospheric photochemical reactions

$$\begin{aligned} &= 0.006 \text{ W/sq.cm} \times 0.5 \times 5.1(E14) \text{ sq.cm} \times 3.15(E7) \text{ sec/yr} \\ &= 482(E21) \text{ J/yr} \end{aligned}$$

E. All direct heating processes:

The solar input to all direct heating processes is estimated from the difference between the total solar energy absorbed by the earth-atmosphere system and that amount which is harnessed in photochemical reactions.

Hence, total solar input to all direct heating processes

$$=3655 - (5 + 482)$$

$$=3168 (E21) \text{ J/yr}$$

F. Other atmospheric heating:

This is a residual heating term and is estimated from the difference between the total solar energy absorbed in the atmosphere and that which is absorbed by clouds or taken up with atmospheric photochemical reactions.

Total absorbed by the atmosphere = 973(E21) J/yr (from Appendix I); Total absorbed by clouds = 151(E21) J/yr (from Appendix I); Atmospheric photochemical reactions = 482(E21) J/yr (see Footnote D, Table 1).

Hence residual heating term:

$$=973 - (151 + 482)$$

$$=340 (E21) \text{ J/yr}$$

G. Direct heating flux absorbed at the earth's surface:

This is estimated from the difference between the total solar input to all direct heating processes and that which is absorbed by clouds and other atmospheric heating.

Total input to direct heating processes = 3168(E21) J/yr (see Footnote E, Table 1); Clouds and other atmospheric heating = 491(E21) J/yr (see Footnote F, Table 1)

Hence residual heating term:

$$=3168 - 491$$

$$=2677 (E21) \text{ J/yr}$$

Alternatively, this term can be estimated from the total solar input absorbed at the earth's surface minus that which is harnessed in biological photosynthesis.

Total absorbed at the earth's surface = 2682(E21) J/yr (see Appendix I); Input to biological photosynthesis = 5(E21) J/yr (see Footnote C, Table 1)

Hence residual heating term:

$$=2682 - 5$$

$$=2677 (E21) \text{ J/yr}$$

H.Direct Heating flux absorbed at land surface and

 ocean surface:

Division of surface absorption flux between land and oceans was estimated on the basis of the surface area ratio, land:ocean = 29%:71% (Times Atlas,1974)

Hence absorption at land surface:

$$\begin{aligned} &= 0.29 \times 2677 \text{ (E21)} \\ &= 776 \text{ (E21) J/yr} \end{aligned}$$

and absorption at ocean surface:

$$\begin{aligned} &= 0.71 \times 2677 \text{ (E21)} \\ &= 1901 \text{ (E21) J/yr} \end{aligned}$$

I. Input to evaporation:

Total solar input to evaporation = 1249 (E21) J/yr (see Footnote A, Table 2). This flux was divided between land and ocean according to their mean relative evaporative fluxes estimated by Sellers (1965) to be in the ratio 410mm/yr:1250mm/yr or 25% : 75%

Hence input to evaporation on land:

$$\begin{aligned} &= 0.25 \times 1249 \text{ (E21)} \\ &= 312 \text{ (E21) J/yr} \end{aligned}$$

and input to evaporation from the oceans:

$$\begin{aligned} &= 0.75 \times 1249 \text{ (E21)} \\ &= 937 \text{ (E21) J/yr} \end{aligned}$$

J. Input to elevating water:

Total solar input to elevating water = 30.7 (E21) J/yr (see Footnote B, Table 2). This flux was divided between the regions of land and ocean in the same manner as was the input to evaporation.

Hence input to elevating water from land:

$$\begin{aligned} &= 0.25 \times 30.7 \text{ (E21)} \\ &= 8 \text{ (E21) J/yr} \end{aligned}$$

and input to elevating water from the oceans:

$$=0.75 \times 30.7 (E21)$$

$$=23 (E21) \text{ J/yr}$$

K. Input to other surface heating:

This is a residual direct heating term. It is estimated from the difference between the total direct heating flux absorbed at the surface and that which is harnessed in evaporation and elevation of water.

Hence the residual heating flux for land:

$$=776 - (312 + 8)$$

$$=456 (E21) \text{ J/yr}$$

and the residual heating flux for oceans:

$$=1901 - (937 + 23)$$

$$=941 (E21) \text{ J/yr}$$

(2)

REDISTRIBUTION OF ABSORBED SOLAR ENERGY
VIA
GLOBAL ENVIRONMENTAL ENERGY FLUXES.

Direct heating by the sun gives rise to redistribution fluxes in the fluid regions of the earth-atmosphere system in order to equilibrate temperature, pressure and concentration differences. The disposition of incoming solar energy to these fluxes is estimated. The "first law" (heat equivalent) fluxes are also given, leading to estimates of Energy Transformation Ratios.

TABLE 2

Redistributive energy flux	Mean Annual Solar Input	Mean Annual 1st law Flux	ETR	Mean Annual Flux*	Foot note
	J (E21)	J (E21)	SCJ/J	SCJ (E21)	
Water flow in hydrologic cycle:					
Chem.Pot.energy of water purity	1280	2.43	822	1997	A
Grav.Pot.energy of elevated water		2.42	825		A
Kinetic energy of wind	473.5	114	6.48	739	B
Kinetic energy of waves	473.5	0.23	3212	739	C
Embodied energy of ocean currents	941	-	-	1468	D
Embodied energy in products of photochemical reactions	487	-	-	760	E
Total absorbed by earth-atmosphere system	3655			5703	G
Solar Constant				5688	

* These figures are estimates of the incoming solar radiation incident on the surface of the atmosphere that is embodied in each of the principal environmental fluxes.

FOOTNOTES TO TABLE 2

A. Chemical Potential energy of water purity:

Water is purified during evaporation and thus gains the potential to dissolve other substances and thereby transport them later in its cycle. When water vapour condenses as clouds in the atmosphere it is pure. The chemical potential energy of water purity is evaluated as the change in Gibbs Free energy between its concentration in the oceans, 3.5% salts (Ehrlich et al., 1977), and its concentration in

rainwater reaching the surface of the land, 3ppm of salts (Saunders,1978) in New Zealand.

$$\Delta F = nRT \ln(C_2/C_1)$$

n = number of moles
 = 1/18 per gram of water
 T = ambient temperature
 = mean temperature for the earth's surface
 = 288 K (Ehrlich et al.,1977)
 R = universal gas constant
 = 8.314 J/gm.mole K

Hence the change in Gibbs Free energy per gram of water:

$$= \frac{(8.314 \text{ J/gm.mole K}) (288 \text{ K})}{(18 \text{ g/gm.mole})} \times \ln \frac{99.9997}{96.5}$$

$$= 4.74 \text{ J/g}$$

Annual precipitation = 1.004m (Sellers,1965); Area of the earth's surface = 5.1(E14) sq.m; Density of water = 1000 kg/cu.m

Hence mean annual global rainfall:

$$= \text{volume of precipitation} \times \text{density}$$

$$= (1.004\text{m}) (5.1\text{E}14 \text{ sq.m}) (1000 \text{ kg/cu.m})$$

$$= 5.12(\text{E}17) \text{ kg/yr}$$

Hence "first law" chemical potential energy flux of global rainfall:

$$= (4.74 \text{ J/g}) (5.12\text{E}20 \text{ g/yr})$$

$$= 2.43(\text{E}21) \text{ J chem. pot./yr}$$

The solar input to purifying water is evaluated as the energy required to evaporate the water (Assumption: total evaporation is equal to total precipitation)

Enthalpy of phase change at atmospheric pressure = 2.44(E6) J/kg (Ehrlich et al.,1977)

Hence solar energy required to evaporate this water:

$$\begin{aligned}
 &= \text{mass of water} \times \text{enthalpy change} \\
 &= (5.12\text{E}17 \text{ kg/yr}) (2.44\text{E}6 \text{ J/kg}) \\
 &= 1249 (\text{E}21) \text{ J/yr}
 \end{aligned}$$

Gravitational Potential energy of elevated water:

Water evaporated from the earth's surface rises through the atmosphere to the point where it condenses into clouds. Subsequently it cools, agglomerates, and falls to earth as rain, releasing energy to the atmosphere. When it reaches earth, it still has the capacity to do useful mechanical work by virtue of its stored gravitational potential energy.

$$\begin{aligned}
 \text{P.E.} &= m \times g \times \Delta h \\
 m &= 5.12(\text{E}17) \text{ kg/yr} \\
 g &= 9.8 \text{ m/sec/sec} \\
 h &= \text{mean elevation of land surface in N.Z.} \\
 &= 483 \text{ m (Reilly, 1965)}
 \end{aligned}$$

Hence the mean annual "first law" flux of gravitational potential associated with water at the mean elevation of the New Zealand land surface:

$$\begin{aligned}
 &= (5.12\text{E}17 \text{ kg/yr}) (9.8 \text{ m/sec/sec}) (483 \text{ m}) \\
 &= 2.42(\text{E}21) \text{ J elevated water/yr}
 \end{aligned}$$

Since the water cycle occurs within the troposphere, the solar input to elevating water is estimated as the energy necessary to heat the water vapour from the mean temperature at an altitude of 9 km (three-quarters of the altitude of the tropopause) to the mean temperature at the earth's surface.

The energy absorbed by water after it has been evaporated:

$$\begin{aligned}
 &= m \times C_p \times \Delta T \\
 T &= 60 \text{ K (Ehrlich et al., 1977)} \\
 C_p(\text{water}) &= 1000 \text{ J/kg K @ 273 K}
 \end{aligned}$$

Hence the mean solar input to elevating water:

$$\begin{aligned}
 &= (5.12\text{E}17 \text{ kg/yr}) (1000 \text{ J/kg K}) (60 \text{ K}) \\
 &= 30.7(\text{E}21) \text{ J/yr}
 \end{aligned}$$

ETRs for water purity and elevated water:

Solar input to evaporating AND lifting the earth's annual rainfall:

$$\begin{aligned} &= (1249 + 31) \times (E21) \text{ J/yr} \\ &= 1280(E21) \text{ J/yr} \end{aligned}$$

This is the embodied energy of total world rainfall. Water has two different sorts of potential, which are coincident but NOT MUTUALLY DEPENDENT. These are the Chemical potential energy of water purity and the Gravitational potential energy of elevated water. We can evaluate two ETRs separately, using the same total solar input, without implying any double-counting of solar energy. In subsequent energetic analysis, the choice of appropriate ETR will depend upon which potential or characteristic of water is of prime concern.

In calculating ETRs based on the solar constant (i.e. in SCJ), it is necessary to multiply by the additional factor of $5688/3655 = 1.56$, being the ratio of the solar constant incident at the surface of the atmosphere to the solar radiation absorbed by the earth-atmosphere system.

BY DEFINITION: $\text{ETR} = (\text{solar energy input}/\text{"first law" energy flow})$

Hence, for water purity:

$$\begin{aligned} \text{ETR} &= \frac{(1280E21 \text{ J/yr})(1.56)}{(2.43E21 \text{ J chem. pot./yr})} \\ &= 822 \text{ SCJ/J chem. pot. of water purity} \end{aligned}$$

and, for elevated water:

$$\begin{aligned} \text{ETR} &= \frac{(1280E21 \text{ J/yr})(1.56)}{(2.42E21 \text{ J grav. pot./yr})} \\ &= 825 \text{ SCJ/J grav. pot. of elevated water} \end{aligned}$$

Alternatively, the embodied energy per unit mass of water can be evaluated:

$$\begin{aligned}
 &= \frac{(1280E21 \text{ J/yr}) (1.56)}{(5.12E17 \text{ kg rainwater/yr})} \\
 &= 3.9(E6) \text{ SCJ/kg rainwater}
 \end{aligned}$$

Hence, the mean annual embodied energy flux of rainwater:

$$\begin{aligned}
 &= (3.9E6 \text{ SCJ/kg}) (5.12E17 \text{ kg/yr}) \\
 &= 1997(E21) \text{ SCJ/yr}
 \end{aligned}$$

B. Kinetic energy of wind:

In the context of the instantaneous energy flux "snapshot" presented here, since winds are gross atmospheric convection currents, they derive their solar energy input in the first instance from the direct heating component in the same way as ocean currents do. To avoid double-counting, the solar input to the hydrologic cycle must be subtracted from the direct heating flux. A further assumption is made that the solar input to winds and to ocean currents in the first instance is divided according to the direct heating of the of atmosphere and land (for winds) and of oceans (for ocean currents). Finally, since ocean waves are generated almost entirely as a result of the action of winds (ehrlich et al., 1977) and since no quantitative description of the wind/wave interaction has been found, the instantaneous solar inputs have been shared equally so as to avoid double-counting.

Gustavson (1979) provides an estimate of the annual energy flux dissipated by winds as being 2.0% of the incoming solar radiation - generation is assumed equal to dissipation.

Hence mean annual "first law" flux of global winds:

$$\begin{aligned}
 &= (5688E21 \text{ J/yr}) (0.02) \\
 &= 114(E21) \text{ J wind/yr}
 \end{aligned}$$

ETR for the kinetic energy of wind:

Solar input to wind is assumed to be half the input to

direct heating of clouds, the atmosphere and the land surface.

Hence mean annual solar input to the generation of winds:

$$\begin{aligned} &= (0.5)(151 + 340 + 456)(E21) \\ &= 473.5(E21) \text{ J/yr} \end{aligned}$$

ETR for the kinetic energy of winds:

$$\begin{aligned} &(473.5E21)(1.56) \text{ J/yr} \\ &= \frac{\text{-----}}{(114E21 \text{ J wind/yr})} \\ &= 6.48 \text{ SCJ/J wind} \end{aligned}$$

Annual flux expressed in SCJ:

$$\begin{aligned} &= (6.48)(114E21) \\ &= 738(E21) \text{ SCJ/yr} \end{aligned}$$

C. Kinetic energy of waves:

--- -----

Kinsman (1965) gives the following expression for power delivered across a shoreline of length "s" by waves of height "h":

$$P_s = \left(\frac{1}{8} \rho g h \right) \left(\frac{g}{2\pi} T \right) \left(\frac{1}{2} \right) S$$

ρ = density of seawater = 1027 kg/cu.m (Ehrlich et al., 1977); g = 9.8 m/sec/sec; h = mean wave height = 1.22 m (Kinsman, 1965); T = wave period = 11.3 seconds (Inman, 1974); s = exposed shoreline of the world = 4.39(E8) m (Inman, 1974).

Hence the mean annual "first law" flux:

$$\begin{aligned} P_s &= \left[\frac{1}{8} \times 1027 \times 9.8 \times (1.22)^2 \right] \left[\frac{9.8}{2\pi} \times 11.3 \right] \left[\frac{3.15(E7)}{2} \right] 4.39(E8) \\ &= 0.23(E21) \text{ J wave/yr} \end{aligned}$$

ETR for the kinetic energy of waves:

--- -----

As indicated in Footnote B above, the solar input to

waves has been shared equally with winds.

Mean annual solar input to waves:

$$= 473.5 (E21) \text{ J/yr}$$

Hence ETR for the kinetic energy of waves:

$$= \frac{(473.5E21 \text{ J/yr}) (1.56)}{(0.23E21 \text{ J wave/yr})}$$

$$= 3212 \text{ SCJ/J wave}$$

Mean annual flux expressed in SCJ:

$$= (3211) (0.23E21)$$

$$= 739 (E21) \text{ SCJ/yr}$$

D. Embodied energy of ocean currents:

This is taken as the residual heating input to oceans = 941(E21) J/yr (from Table 1).

Hence mean annual flux expressed in SCJ:

$$= (941E21) (1.56)$$

$$= 1468 (E21) \text{ SCJ/yr}$$

E. Embodied energy in products of photochemical

 reactions:

Input to photochemical reactions = 487(E21) J/yr (from Table 1).

Hence mean annual flux expressed in SCJ:

$$= (487E21) (1.56)$$

$$= 760 (E21) \text{ SCJ/yr}$$

F.Discrepancy:

Mean value of the Solar Constant = 5688(E21) SCJ/yr (from Appendix I). Total of the environmental energy fluxes expressed in SCJ = 5700(E21) SCJ/yr. This 0.3% discrepancy is due to the rounding off of figures. It is negligible compared with other sources of error.

(3)
 "FIRST" LAW ESTIMATES

 OF THE MAJOR ENVIRONMENTAL ENERGY FLUXES
 -- -- --
 FLOWING INTO NEW ZEALAND

TABLE 3

Energy type	Mean annual energy flux J (E18)	Foot note
Solar energy incident on land surface	1386.3	A
Solar energy absorbed by land surface	1081.3	B
Solar energy used to evaporate water	393.2	C
Wind energy absorbed in N.Z.	39.2	D
Gravitational potential energy of elev.water	1.9	E
Chemical potential energy of precipitation	2.6	F
Chemical potential energy of precn.-evapn.	1.8	G
Wave energy incident on the shores	5.2	H
Tidal energy absorbed on the shelf	0.1	I
Geologic uplift	2.4 (E-7)	J

FOOTNOTES TO TABLE 3

A.Solar energy incident on the land surface:

Mean daily insolation for New Zealand = 336.65 Ly/day (De Lisle, 1966) = 14.11 MJ/sq.m/day; Area of New Zealand = 2.69 (E11) sq.m (N.Z.Official Yrbk., 1978).

Hence mean annual insolation:

$$= (14.11E6 \text{ J/sq.m/day}) (2.69E11 \text{ sq.m}) (365.25)$$

$$\text{days/yr}) = 1386.3(E18) \text{ J/yr}$$

B. Solar energy absorbed by the land surface:

Estimates of the albedos (Sellers, 1965) = 0.25 for 13.5(E6) ha - pasture and arable land; = 0.10 for 7.0(E6) ha - forested land; = 0.28 for 6.4(E6) ha - remainder. These estimates yield a mean value of the albedo of 0.22 .

Hence absorption of solar energy at the land surface:

$$\begin{aligned} &= (0.78)(1386.3E18 \text{ J/yr}) \\ &= 1081.3(E18) \text{ J/yr} \end{aligned}$$

C. Solar energy used to evaporate water:

Mean annual evaporation from N.Z. = 0.599 m (Toebes, 1972); Energy required to evaporate water at atmospheric pressure = $2.44E3 \text{ J/g}$ (Ehrlich et al., 1977).

Hence evaporative energy flux for N.Z.:

$$\begin{aligned} &= (2.69E11 \text{ sq.m})(0.599 \text{ m}) \\ &\quad \times (1E6 \text{ g/cu.m})(2.44E3 \text{ J/g}) \\ &= 393.2(E18) \text{ J/yr} \end{aligned}$$

D. Wind energy absorbed in New Zealand:

An overall westerly airflow was assumed - also that "wind energy out" minus "wind energy in" is equal to the wind energy absorbed - i.e. the energy dissipated by wind over the New Zealand land mass = $(E_{in} - E_{out})(\text{length of island})(\text{boundary depth})$.

Using data from Cherry(1978) for the North Island:

$$\begin{aligned} E &= (640-330 \text{ W/sq.m})(3.15E7 \text{ secs/yr}) \\ &\quad \times (7.5E5 \text{ m})(2000\text{m}) \\ &= 14.648(E18) \text{ J/yr} \end{aligned}$$

and for the South Island:

$$\begin{aligned} E &= (850-330 \text{ W/sq.m})(3.15E7 \text{ secs/yr}) \\ &\quad \times (7.5E5 \text{ m})(2000\text{m}) \\ &= 24.570(E18) \text{ J/yr} \end{aligned}$$

Hence the total annual wind energy flux for New Zealand:

$$= 39.2(E18) \text{ J/yr}$$

E.Gravitational potential energy of elevated water:

Mean annual precipitation for New Zealand = 2.059 m (Toebees,1972); Mean annual evaporation for New Zealand = 0.599 m (Toebees,1972); Mean height of land in New Zealand = 483 m (Reilly,1965); Area of New Zealand = 2.69(E11)sq.m (N.Z.Official Yrbk,1978). Gravitational potential energy stored = m x g x h.

Hence the mean annual flux of gravitational potential energy derived from elevated water:

$$\begin{aligned} &= (2.059-0.599\text{cu.m/sq.m/yr}) (2.69\text{E11sq.m}) (483\text{m}) \\ &\quad \times (1000\text{kg/cu.m}) (9.8\text{m/sec/sec}) \\ &= 1.859(E18) \text{ J/yr} \end{aligned}$$

F.Chemical potential energy of precipitation:

F for rainwater = 4.74 J/g (Footnote A to Table 2); Mean annual mass of precipitation in New Zealand = (2.059cu.m/sq.m/yr)(2.69E11 sq.m)(1E6 g/cu.m) = 5.539(E17) g/yr.

Hence the mean annual flux of chemical potential energy derived from purified rainwater:

$$\begin{aligned} &= (5.539E17 \text{ J/g}) (4.74 \text{ J/g}) \\ &= 2.625(E18) \text{ J/yr} \end{aligned}$$

G.Chemical potential energy of precipitation minus evaporation:

Mean annual net precipitation in New Zealand = (2.059-0.599cu.m/sq.m/yr) (2.69E11sq.m) (1E6 g/cu.m) = 3.927(E17) g/yr.

Corresponding mean annual flux of chemical potential energy;

$$\begin{aligned} &= (3.927E17 \text{ g/yr}) (4.74 \text{ J/g}) \\ &= 1.862(E18) \text{ J/yr} \end{aligned}$$

H. Wave energy incident on the shores of New Zealand:

ESTIMATE ONE

Shoreline of the world = 4.39 (E8) m (Inman, 1974);
 Shoreline of New Zealand = 1.0 (E7) m (R.M. Kirk, Pers. Comm.);
 Wave energy incident on world shores = 2.3 (E20) J/yr
 (Footnote D, Table 2).

Hence wave energy incident on New Zealand shores:

$$= \left[\frac{1.0 (E7)}{4.39 (E8)} \right] (2.3 E20)$$

$$= 5.24 (E18) \text{ J/yr}$$

ESTIMATE TWO

Mean power of waves measured in Taranaki Bight at Maui
 A platform = 25 kW/m wave length (R.M. Kirk, Pers. Comm.).

Hence wave energy incident on New Zealand shores:

$$= (1.0 E7 \text{ m}) (2.5 E4 \text{ W/m}) (3.15 E7 \text{ secs/yr})$$

$$= 7.88 (E18) \text{ J/yr}$$

N.B. The smaller of the two estimates was used because
 of uncertainty about the appropriate length of shoreline for
 New Zealand.

I. Tidal energy absorbed on New Zealand's continental
 shelf:

Mean tidal amplitude = 1.2 m (R.M. Kirk, Pers. Comm.);
 Percentage of tidal energy absorbed = 10%
 (R.M. Kirk, Pers. Comm.); Absorbing area assumed to be the
 shelf out to a depth of 200m = 2.49 (E11) sq.m (Reilly, 1965);
 Number of tides per year = 705; The energy absorbed per
 tide is given by the equation

$$\text{energy/tide} = \frac{1}{2} \rho g h^2 A$$

(kinetic energy only).

Hence the mean annual flux of energy absorbed from
 tides around New Zealand's continental shelf:

$$\begin{aligned}
 &= (0.5)(0.1)(1.027E3\text{kg/cu.m}) \\
 &\quad \times (9.8\text{m/sec/sec})(1.2\text{m})(1.2\text{m}) \\
 &\quad \times (2.49E11\text{sq.m})(705) \\
 &= 1.27(E17) \text{ J/yr}
 \end{aligned}$$

J. Energy of geologic uplift for New Zealand:

Mean annual rate of geologic uplift for New Zealand = 1.5mm/yr (Adams, 1978); Area of New Zealand's tectonic plate = $4(E12)\text{sq.m}$ (Stevens, 1980); Density of Sial = 2.7g/cu.cm (Stevens, 1980). Therefore the mass of earth's crust that is lifted by geo-mechanical action = $(0.0015\text{m/yr})(4E12\text{sq.m})(2.7E6\text{g/cu.m}) = 1.62(E16)\text{g/yr}$.

The energy expended in this uplift:

$$\begin{aligned}
 &= m \times g \times \Delta h \\
 &= (1.62E13\text{kg/yr})(0.0015\text{m/yr})(9.8\text{m/sec/sec}) \\
 &= 2.38(E11) \text{ J/yr}
 \end{aligned}$$

(4)

ANNUAL ENVIRONMENTAL ENERGY INPUT
TO THE
NEW ZEALAND SYSTEM

Because of its geographical location and shape, New Zealand receives more than its share of global environmental energy fluxes as might be calculated on a pro rata area basis. Hence the effective environmental inputs to New Zealand were evaluated as the sum of the Direct Insolation absorbed by New Zealand's land surface and in the vertical column of the atmosphere above it, the gravitational potential energy derived from the geological uplift in the tectonic plate of which New Zealand is a part, the kinetic energy from tides impinging on the coastline and the energies from excess rain, excess wind and excess waves that New Zealand receives over and above its world average pro rata share.

TABLE 4

Energy type	Mean annual First Law Flux J (E18)	Expressed in Solar Constant Joules SCJ (E21)	Footnote
Direct Solar	1472	2.30	A
Geologic uplift	2.4 (E-7)	0.00	B
Excess Rain	284.1 (E12) kg	1.11	C
Excess Wind	16.9	0.11	D
Tides	0.1	0.14	E
Excess Waves	0.0	0.00	F
Total Environmental Inflow		3.66	G

FOOTNOTES TO TABLE 4

A. Direct Solar input:

Solar energy absorbed by land surface = $1.081(E21)$ J/yr (Table 3); Scaled up to include the direct insolation absorbed in the vertical column of atmosphere above the land by using % figures from Appendix 1 - Total solar radiation absorbed by earth-atmosphere system = 64%; Total absorbed at the earth's surface = 47%.

Hence the Direct Solar input to New Zealand:

$$= (1.081E21) (64/47)$$

$$= 1.472(E21) \text{ J/yr}$$

Expressed in Solar Constant Joules:

$$= 1.472(E21) \times 1.56$$

$$= 2.296(E21) \text{ SCJ/yr}$$

B. Geologic Uplift:

It is important to realise that this is not a real ETR but a notional or equivalent ETR insofar as the uplift part of the geologic cycle (uplift --> erosion --> sedimentation) is not driven by solar energy alone. The isostatic forces that result in geologic uplift are generated by a

combination of the actions of core heat and solar energy driving the erosion processes on the earth's surface. Since this solar input has already been accounted for once (as inputs to the weathering flows of winds, rain and waves) it is not counted here again and the notional ETR for geologic uplift is based on core heat alone.

It was assumed that the fusion reactions occurring in the earth's core at 5000 degrees celsius (Times Atlas, 1974) are similar to those occurring in the sun at 6000 degrees celsius and that their heat output is of similar quality. Hence the assumption was made - 1 SCJ = 1.2 J core heat.

Hayakawa (1976) estimated that the energy consumed in geologic uplift for the world = 0.025 kcal/sq.m/day = 0.0195 (E21) J core heat/yr; Hubbert (1971) estimated the total core heat flow from the centre of the earth = 32 (E12) W = 1.008 (E21) J core heat/yr.

Hence the notional ETR for geologic uplift:

$$\begin{aligned} & 1.008 \text{ (E21) J core heat} \\ & = \frac{\text{-----}}{0.0195 \text{ (E21) J uplift}} \\ & = 51.7 \text{ J core heat/J uplift} \\ & = 43.0 \text{ SCJ / J uplift} \end{aligned}$$

Total energy flow into New Zealand expended in geologic uplift:

$$= 2.38 \text{ (E11) J uplift/yr (Table 3)}$$

Expressed in Solar Constant Joules:

$$\begin{aligned} & = 2.38 \text{ (E11) J uplift/yr} \times 43.0 \text{ SCJ/J uplift} \\ & = 1.02 \text{ (E13) SCJ/yr} \\ & (= 0.00 \text{ (E21) SCJ/yr}) \end{aligned}$$

C.Excess Rain:

Mean annual world rainfall = 5.12 (E17) kg/yr (Footnote A, Table 2); Area of the earth's surface = 5.1 (E14) sq.m (Ehrlich et al.,1977); Area of New Zealand land surface = 2.69 (E11) sq.m (N.Z. Official Yrbk,1978) = 0.0527 % of the earth's surface.

Hence, on a pro rata land area basis, New Zealand's share of the mean annual world rainfall:

$$= (5.12E17 \text{ kg/yr}) (0.000527)$$

$$= 269.8 \text{ (E12) kg/yr}$$

Actual mean annual rainfall in New Zealand = 553.9 (E12) kg/yr (Footnote F, Table 3).

Hence New Zealand's rainfall over and above the world mean value:

$$= (553.9 - 269.8) \text{ (E12) kg/yr}$$

$$= 284.1 \text{ (E12) kg/yr}$$

Expressed in Solar Constant Joules:

$$= 284.1 \text{ (E12) kg/yr} \times 3.9 \text{ (E6) SCJ/kg}$$

$$= 1.11 \text{ (E21) SCJ/yr}$$

D.Excess Wind:

Total global wind energy dissipation per year = 1.14 (E23) J (Gustavson, 1979); 35% of this wind energy dissipation occurs in the lower 1km and between 31% and 32% is dissipated at the surface boundary (Gustavson, 1979); It was assumed here that approximately 37% of the world's wind energy is dissipated in the lower 2km of the atmosphere:

$$(0.37) (1.14E23 \text{ J/yr})$$

$$= \frac{\text{-----}}{(5.1E14 \text{ sq.m})}$$

$$= 82.7 \text{ MJ/sq.m/yr}$$

In New Zealand the wind energy dissipation in the lower 2km = 39.2 (E18) J/yr (Footnote D, Table 3):

$$39.2 \text{ (E18) J/yr}$$

$$= \frac{\text{-----}}{2.69 \text{ (E11) sq.m}}$$

$$= 145.7 \text{ MJ/sq.m/yr}$$

Hence the excess wind energy dissipated in New Zealand:

$$= ((145.7 - 82.7) \text{ MJ/sq.m/yr}) (2.69 \text{ E11 sq.m})$$

$$= 16.9 \text{ (E18) J/yr}$$

Expressed in Solar Constant Joules:

$$= 16.9 (E18) \text{ J wind/yr} \times 6.48 \text{ SCJ/J wind}$$

$$= 0.11 (E21) \text{ SCJ/yr}$$

E.Tides:

Mean value of tidal energy actually absorbed on New Zealand's shoreline = 1.27 (E17) J/yr (Footnote I, Table 3).

ETR for Tidal energy.

--- --- -----

Since tides are caused by gravitational interactions mainly between the earth and the moon, this ETR is only a notional ETR. The ETR for SCJ to J tidal is derived by combining the ETR for J tidal to J electricity and the ETR for SCJ to J electricity via a hydro-electric scheme.

ETR for SCJ to J electricity

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New Zealand's dominant source of electricity is stored rainwater. Thus it is appropriate to estimate an ETR for SCJ to J electricity in New Zealand using the hydro-electricity transformation process. For this purpose the Waikato River hydro system was chosen since it is a fully developed system with little potential for further hydro development.

New Zealand Electricity Department has figures for the generating expenses, capital requirements and interest charges associated with the 9 hydro-electric power plants on the Waikato River. These data were used to estimate the embodied energy of the goods and services feedbacks required for hydro-electricity generation on an annual basis. NZED also has data for the total water throughput of the Waikato River system. These were used to estimate the embodied energy derived from elevated water.

Annual generating expenses:

$$= \$3.512\text{m} (\$1978) @ 0.32 (E12) \text{ SCJ}/\$1978$$

$$= 1.12 (E18) \text{ SCJ/yr}$$

Annual interest charges:

$$= \$1.228\text{m} (\$1978) @ 0.32 (E12) \text{ SCJ}/\$1978$$

$$= 0.39 (E18) \text{ SCJ/yr}$$

The embodied energy lost via capital depreciation was estimated as 2.5% of the total capital inputs. For the 9 hydro-electric power plants the estimates were as follows:-

(1) Arapuni (1929): = \$6.666m (\$1929) @ 3.04 (E12) SCJ/\$1929 = 20.26 (E18) SCJ/yr; (2) Lake Taupo Control (1941): = \$0.428m (\$1941) @ 2.11 (E12) SCJ/\$1942 * = 0.90 (E18) SCJ/yr; (3) Karapiro (1947): = \$8.578m (\$1947) @ 1.46 (E12) SCJ/\$1948 * = 12.52 (E18) SCJ/yr; (4) Maraetai (1952): = \$39.528m (\$1952) @ 1.11 (E12) SCJ/\$1952 = 43.88 (E18) SCJ/yr; (5) Whakamaru (1956): = \$21.923m (\$1956) @ 0.91 (E12) SCJ/\$1956 = 19.95 (E18) SCJ/yr; (6) Atiamuri (1958): = \$21.203m (\$1958) @ 0.89 (E12) SCJ/\$1958 = 18.87 (E18) SCJ/yr; (7) Waipapa (1961): = \$15.664m (\$1961) @ 0.80 (E12) SCJ/\$1961 = 12.53 (E18) SCJ/yr; (8) Ohakuri (1961): = \$21.147m (\$1961) @ 0.80 (E12) SCJ/\$1961 = 16.92 (E18) SCJ/yr; (9) Aratiatia (1964): = \$16.154m (\$1964) @ 0.68 (E12) SCJ/\$1964; = 10.98 (E18) SCJ/yr; * For these years corresponding energy-to-dollar ratios were not available. Ratios for the following years have thus been applied giving an error on the conservative side.

Embodied energy of total capital inputs = 156.81 (E18) SCJ/yr.

Hence embodied energy of annual capital depreciation:

$$= (0.025)(156.81 \text{ E18}) \\ = 3.92 \text{ (E18) SCJ/yr}$$

Embodied energy of all goods and services feedbacks = (1.12 + 0.39 + 3.92)(E18) SCJ/yr = 5.43 (E18) SCJ/yr.

Total annual water throughput = (221 cu.m/sec)(3.15 E7 secs/yr) = 6.96 (E9) cu.m/yr.

Hence embodied energy of elevated water:

$$= (6.96 \text{ E9 cu.m/yr})(1000 \text{ kg/cu.m})(3.9 \text{ E6 SCJ/kg}) \\ = 27.144 \text{ (E18) SCJ/yr}$$

Total generated electricity = (4073.6 E6 kWh)(3.6 E6 J/kWh) = 14.665 (E15) J elec./yr.

Hence ETR for hydro-electricity:

$$= \frac{27144 + 5430}{14.665}$$

= 2221 SCJ/J electricity

ETR for J tidal to J electricity

Odum, Kylstra, Alexander et al (1976) estimate the ETR for the transformation from tidal energy to electrical energy = 2.09 J tidal/J electrical.

ETR for SCJ to J Tidal

The resulting notional ETR:

2221 SCJ/J elec.

= -----

2.09 J tidal/J elec.

= 1063 SCJ/J tidal

F.Excess Waves:

Because of uncertainties in the estimate of New Zealand's coastline (Footnote H, Table 3) the marginally lower world mean value was used for estimating New Zealand's pro rata share of wave energy input.

Hence, the excess wave energy over and above the world mean value = 0

G.Total environmental inflow:

Adding the energy fluxes of EXCESS rain, EXCESS wind and EXCESS waves to the direct insolation onto New Zealand avoids double-counting solar energy inputs. Although these other fluxes are all solar driven, their excess levels for New Zealand indicate that this country receives the benefit of global solar input in excess of its pro rata share. In effect, New Zealand benefits directly from insolation impinging on a much larger area of the earth's surface. For example, the vast land mass of Australia contributes a considerable input to the weather systems that affect New Zealand.

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APPENDIX I

 GLOBAL DISPOSITION

 OF THE

 MEAN ANNUAL SOLAR RADIATION

 INCIDENT ON

 THE TOP OF THE ATMOSPHERE

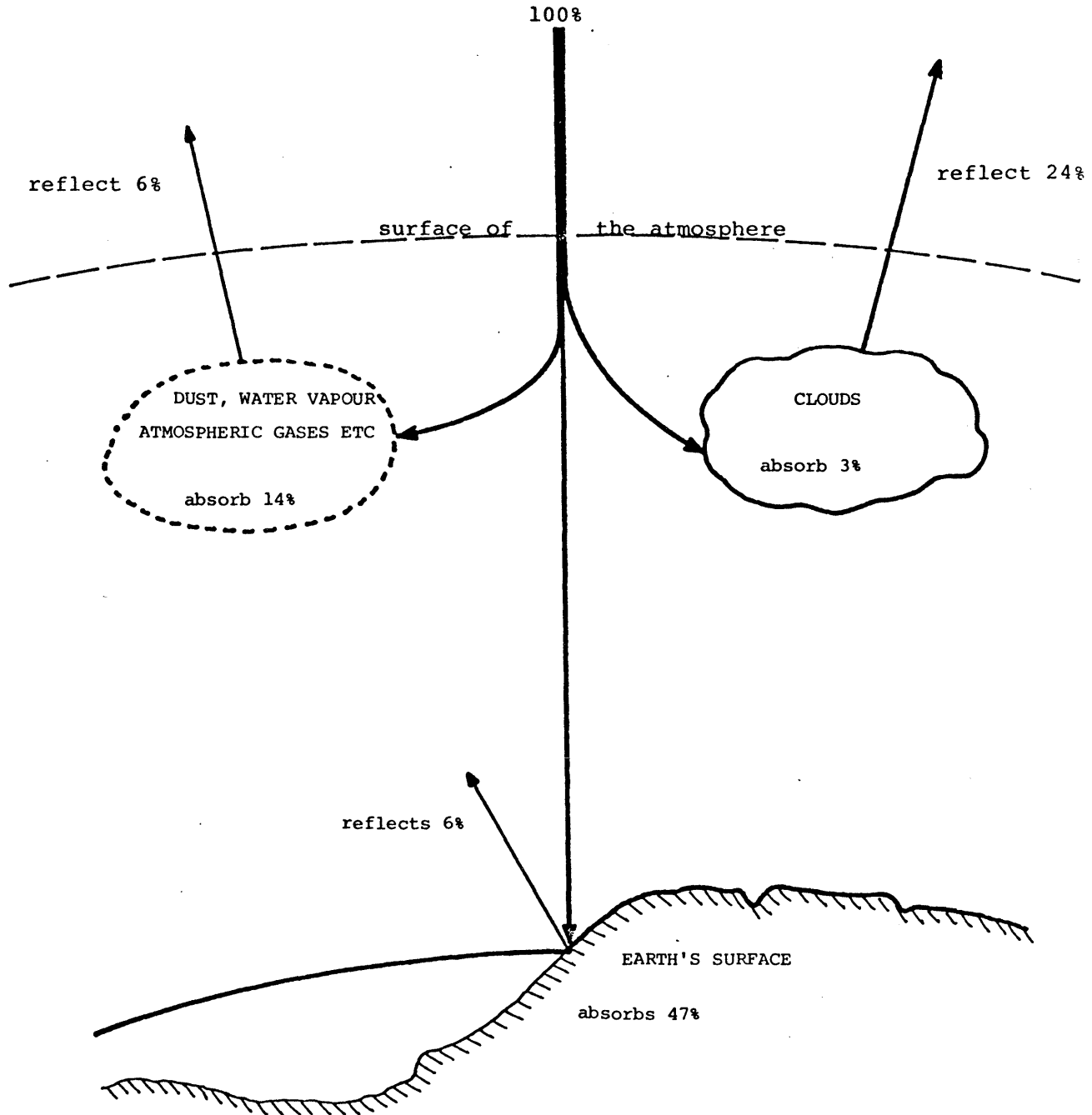
The percentages of incoming solar energy absorbed or reflected at each level in the earth-atmosphere system were taken from Sellers (1965) as the most complete and authoritative description available. The total amount of incoming solar energy (5.688 E24 Joules/yr) was taken from Gustavson (1979)* as probably having the benefit of the most recent satellite measurements of the solar constant. The total incoming solar energy was apportioned according to the percentages given by Sellers (1965).

Description of flux	Mean annual value of the energy flux J (E21)	%
Solar energy incident on top of the atmosphere *	5688	100
Reflected by clouds	1363	24
Reflected by dust, water vapour etc	324	6
Total reflected by the atmosphere	1687	30
Reflected from the earth's surface	346	6
Total reflected by earth-atmosphere system	2033	36
Absorbed by clouds	151	3
Absorbed by dust, water vapour etc	822	14
Total absorbed by the atmosphere	973	17
Absorbed at the earth's surface	2682	47
Total absorbed by earth-atmosphere system	3655	64

- * Intercepted flux
 = 1.8 (E17) W
 = (1.8 E17 J/sec) (3.15 E7 sec/yr)
 = 5688 (E21) J/yr
 designated Solar Constant Joules (SCJ).

Figure 10

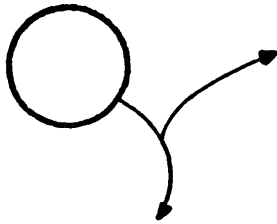
Total intercepted solar energy



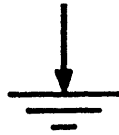
Schematic representation of information contained in Appendix I
Immediate disposition of intercepted solar energy

APPENDIX II

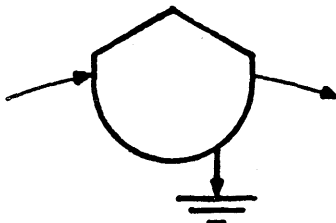
Summary of Energy Symbols
used in the Diagrams



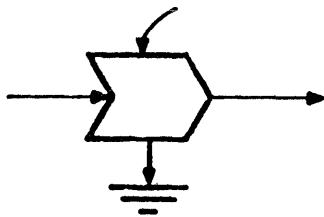
Energy Source with ultimate limit to flow



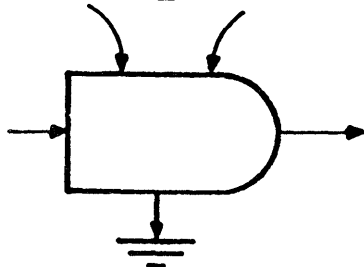
Heat sink - outflow of degraded energy



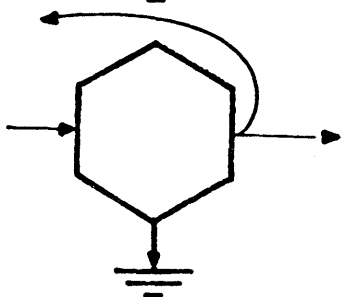
Energy storage



Interaction process of several energy flows



Production subsystem - large inflow of low quality energy which is concentrated for consumption in subsequent processes.



Consumption subsystem - processes driven mainly by inflows of more concentrated energy forms.

