ENERGY SYSTEMS PERSPECTIVES ON
ST. LUCIA

by

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INTRODUCTION

Over the past several decades economic indices have been used to develop economic policies for the welfare of nations. Such policies were successful during this period when energy and environmental resources were available in excess and did not limit development. Without limitation, population, capital, national infrastructure, etc. grew at exponential rates. Now, however, as energy and resources are becoming scarce and begin to affect economic activity more strongly, new public policies that recognize the relationships between resources and national development are required.

Energy analysis is one of several approaches that attempt to relate the prosperity and health of the human economy to the causal externalities that maximize the economies of nature and humanity as a single unit. A new approach to energy analysis is ayplied in this preliminary paper that provides an overview of humanity and nature in St. Lucia, relates St. Lucia to world trends and suggests public policies that coordinate prosperity and resource management in the long run. Some recommendations may run counter to policies that emerged during the earlier period of rapid growth.

Summaries of energy sources and consumption rates of many countries were produced following the energy crises of the 1970's. Generally these consisted of tabulations of volumes and types of fossil fuel consumed and the generation of electricity. Energies associated with other environmental resources that contribute to the economies of nations were not generally evaluated. Solar energy, where studied, was considered only as an input to solar technology. Its value in driving the water cycle, controlling climate, etc. was neglected. In addition, different qualities of energies were not recognized with the exception of electricity being four times as great as fuel (in terms of potential contribution and flexibility) in some studies.

For St. Lucia efforts have been made to evaluate the following external energy sources in units of equivalent embodied energy:

1) Solar derived sources, ie. sun, rain, wind, waves and hurricanes.
2) Geologic sources; material uplift and heat.
3) Tides.
4) Nonrewable sources, ie. fossil fuels and fertilizers.
5) Imported goods and services.
6) Dollars from tourist services.

An energy evaluation of island exports was also done. Subtracting exported energy from the source energies listed above is an estimate of energy consumed within the country.

Previous energetic analyses using these methods have produced several papers recommending alternatives for the United States (Odum et al., 1975 and 1979), showing large trade imbalances for New Zealand as a result of public policy emphasizing export of raw and semi-processed goods (Odum and Odum, 1979), and summarizing energy balances of 30 nations (preliminary class reports, Univ. of Florida, 1980-2). St. Lucia was among this last group of analyses and this report includes an update of that preliminary paper.

Background

St. Lucia lies in the Windward Island chain of the Caribbean. It is tropical in climate and features a variety of ecosystems, from cactus scrub in the lowlands to rain/cloud forests on the interior mountain slopes. The island is 6.16 E8 m^2 in area with a maximum elevation of 3117 m and an average elevation of 262 m above sea level.

The region is subject to relatively high concentrations of natural energy compared to other parts of the globe. Sunlight (over 180 $Cal/cm^2 \cdot yr$)

is intense and provides energy for photosynthesis. Rainfall (over 2 m/yr) contributes chemical potential energies, which dissolve minerals and perform chemical work in plants, and gravitational potential energy which is used to shape and build the landscape. Consisitent trade winds moderate the climate, accelerate gas exchange in the natural ecosystem aiding productivity, and carry moisture which is translated into additional rain in the elevated interior. Waves induced by these winds do work in building beaches and shore features, increasing uplift and the turnover of new materials. The uplifted materials are then converted into rich volcanic soils by the weathering process. Tidal energies, though small due to low heights and a small tidal shelf, do provide nutrients for the coastal systems that contribute seafoods to the island diet.

Hurricanes are important sources of energy which are usually perceived as having negative effects. High winds topple older trees while heavy rains weather more rocks into soil. The overall effect is to pulse the natural ecosystems, accelerate geologic cycles and may thereby increase productivity. At the same time groundwater supplies are renewed.

Geological reports have estimated the size of a large volume of superheated water, also evidenced by a number of hot springs, which appears to be of sufficient size to operate a geothermal power unit for an extended period of time.

The major export industries are plantations producing bananas and coconuts (accounting for 60% of total export dollars) and tourism which has been responsible for more than 50% of all foreign exchange earnings. Other exports that have begun to increase over the past few years include paper products, fruits and spices, hardwoods, garments and electrical hardware.

Most of the developed, urban economy is dependant on imported energies in the form of fossil fuel, primarily diesel of which about 60% is used for power generation, and fertilizers which are consumed almost entirely by plantation operations. All machinery, construction materials and a large volume of foodstuffs (21% of all import dollars) are imported. In contrast, many of the energies reaching rural individuals are direct environmental services operating a subsistence economy with little money circulated.

METHODS

The procedures taken for this analysis are listed below. A detailed manual featuring equations for the calculations of energy flows, examples, transformation ratios and their derivations and rationales for particular approaches is available (Odum et al., 1981). A list of energy language symbols is presented in Figure 1. These symbols reflect energetic constraints, kinetic relationships, macroeconomic flows and causal influences for all dominant island processes. A functional definition is associated with each symbol (Appendix F).

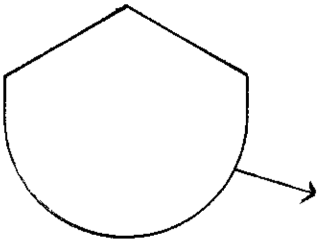
1) Based on information about land use, regional economy and ecosystem principles an overview diagram of St. Lucia was created (Figure 2.).

a) All energy sources (inputs) for the island were listed in order of quality. These include natural energies such as sun, wind, tides, geologic uplift, etc. Processed energies such as fossil fuels and goods and services were also listed. Island output (exports) was included last. Sources were drawn on the diagram from left to right in increasing quality.

b) A list was made of major subsystems which include dominant island ecosystems, three agricultural land uses, three major industries, power conversion and a generalized urban center that implicitly contains government, culture etc. and explicitly contains the island's population and its capital.

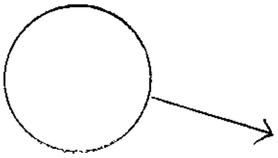
c) Other important storages were included. These are forests, soils, subsurface heat and image. "Image" is generated by an interaction between the hotel industry (and government policy) and the natural elements of the island. Despite its abstractness, ie. the problem of evaluating a quantity of calories stored in such a tank, it is vital in prompting the flux of tourist dollars.

2) Two tables were prepared: one of all dominant flows across the



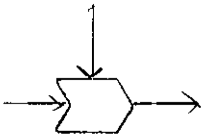
a) Storage

b) Flow

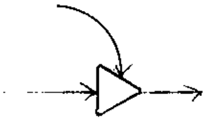


c) Source

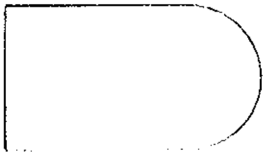
d) Heat Sink



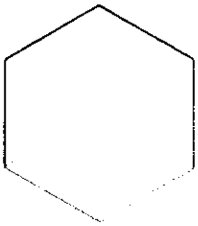
e) Interaction



f) Constant Gain

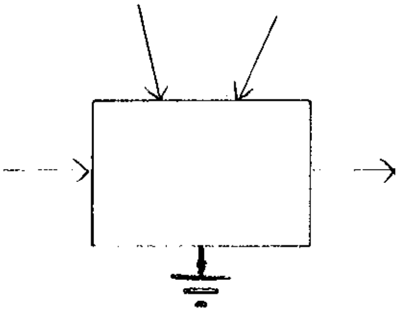


g) Producer

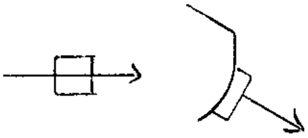


h) Consumer

i) Money Exchange



j) Process



k) sensors

Figure 1. Symbols for Energy Analysis. Accompanies Appendix F.

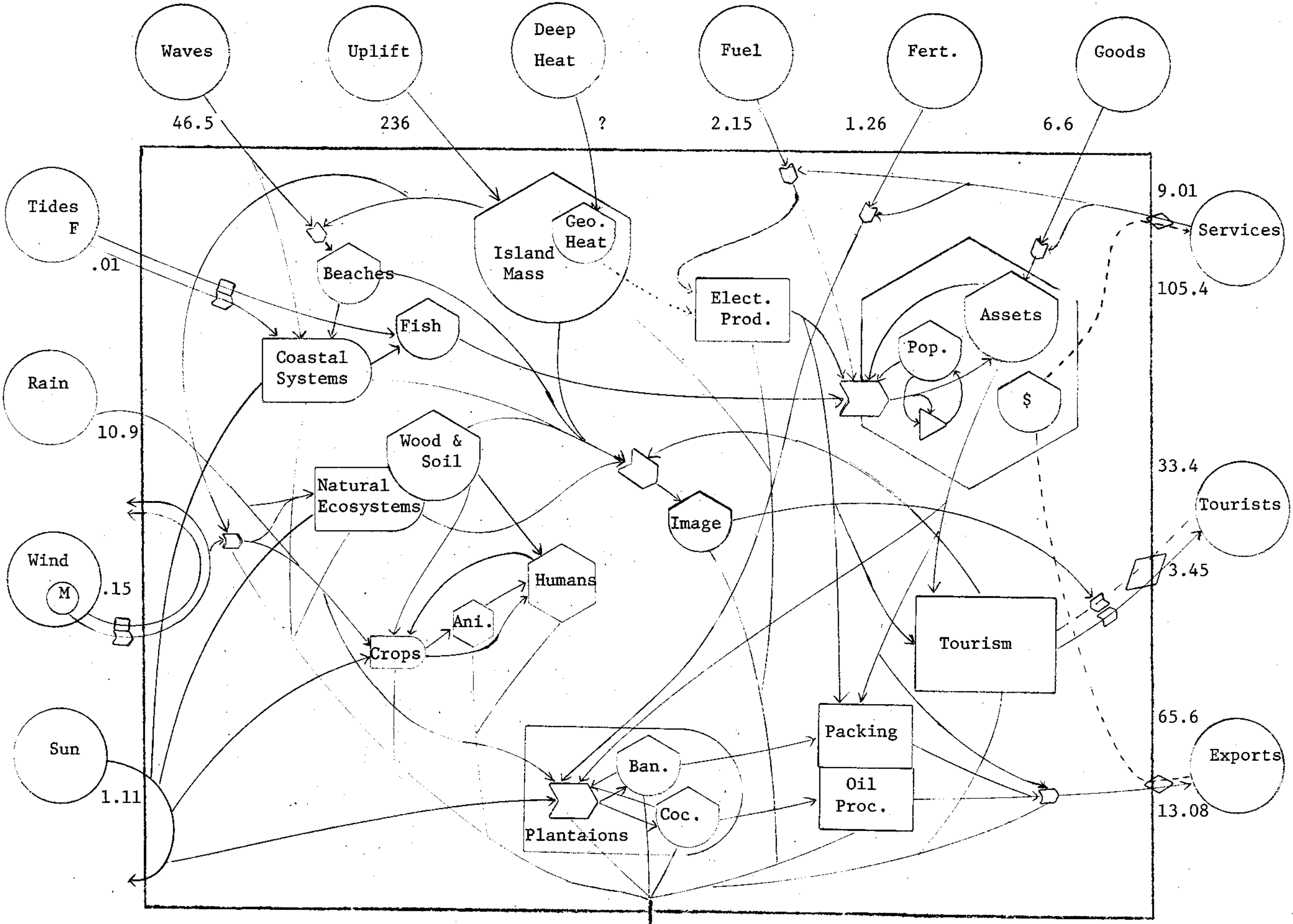


Figure 2. Overview Diagram of St. Lucia

Calorie values times 10^{15} Global Solar Cal.
Dollar values times 10^{6}U.S.

island boundary (Table 1) and one of the dominant storages within the system (Table 2).

a) Using standard formulae of physics, chemistry and geology the actual energy flow or storage for each item in the tables was calculated in actual (heat equivalent) kilocalories.

b) Energy transformation ratios, taken primarily from Odum et al., 1981, were reported in the tables both for global solar calories and for coal equivalent calories. These ratios reflect the total energy required to produce a single calorie associated with a particular element. For example, it requires 6900 calories of sunlight falling on the earth to generate one calorie chemical potential present in rainwater. Derivations for other ratios can be found in the above reference. Since the sun is responsible for most of the energies dealt with it is a more basic common denominator for calculations though many previous analyses especially those examinining fuel consumption worked with fossil fuel (coal) equivalents. The basic method of creating a solar derived ratio was to calculate the total energies of a particular form ie., rain, wind, waves, etc. and divide that value into the total sunlight falling on the globe during an equivalent length of time.

c) Embodied energies, reported in both global solar calories and coal equivalent calories, were calculated by multiplying the actual calories evaluated in part (a) by the transformation ratio associated with that element. The embodied energies provided perspective on what is relatively important to the island, ie. what storages and flows control island processes.

Table 1. Calorie values of major flows.
St. Lucia

Reference Number	Flow	Actual Calories	Global Solar		Coal Equivalent	
			ETR	Embodied (E15)	ETR	Embodied E11
1	Sun	1.11 E 15	1.0	1.11	1.47 E-4	1.63
2	Rain (Chem. Pot.)	1.58 E 12	6.90 E 3	10.9	1.01	16.0
3	Rain (Kin. Pot.)	9.24 E 9	2.38 E 5	2.20	3.50 E 1	3.23
4	Wind	2.63 E 11	5.68 E 2	0.15	8.34 E-2	0.22
5	Runoff (Grav Pot.	4.98 E 11	1.06 E 4	5.28	1.56	7.77
6	Waves	4.01 E 12	1.16 E 4	46.5	1.71	68.6
7	Tides	9.74 E 8	1.16 E 4	0.01	1.71	0.02
8	Uplift (Grav. Pot.)	4.85 E 1	1.50 E 15	72.7	2.21 E 11	92.8
9	Uplift (Chem. Pot.)	1.14 E 10	2.08 E 7	236.0	3.06 E 3	348.0
10	Fuel	3.16 E 11	6.80 E 3	2.15	1.00	3.16
11	Fertilizer (N)	9.75 E 8	1.90 E 5	0.19	2.79 E 1	0.27
12	Fertilizer (P)	5.36 E 8	1.99 E 6	1.07	2.93 E 2	1.57
13	Imported Goods	2.80 E 11	---	6.60	---	9.71
14	Services	---	---	7.96	---	11.7
15	Cost of Fuel	---	---	0.97	---	1.42
16	Cost of Fertilizer	---	---	0.09	---	0.13
17	Exports (Goods)	---	---	1.88	---	2.76

Table 1 (cont.)

Reference Number	Flow	Actual Calories	Global Solar		Coal Equivalent	
			ETR	Embodied (E15)	ETR	Embodied (E11)
18	Electricity	4.86 E 10	2.72 E 4	1.32	4.00	1.94
19	Exported Services	---	---	9.29	---	16.4
20	Tourism	---	---	2.82	---	4.14
*	Hurricanes	8.96 E 11	3.72 E 4	33.3	5.47	49.0

Imports and Exports are 1978 figures

Embodied value of imported goods is not complete

Calorie content of potash (K) fertilizer excluded

Table 2. Calorie value of dominant island storages.

St. Lucia

Reference Number	Storage	Actual Calories	Global Solar		Coal Equivalent	
			ETR	Embodied	ETR	Embodied
1	Soil	5.01 E12	35.3 E4	1.77 E18	5.19 E1	2.6 E14
2	Chem. Pot. of Base Rock	1.99 E16	2.08 E7	4.13 E23	3.06 E3	6.07 E19
3	Grav. Pot. of Uplifted Land	1.48 E14	1.50 E15	2.22 E29	2.21 E11	3.27 E25
4	Biomass	2.84 E13	2.89 E3	8.19 E16	4.25 E1	1.21 E13
5	Electrical Structure	1.99 E11	6.80 E3	1.35 E15	1.00	1.99 E11
6	Roads	1.14 E12	6.80 E3	7.76 E15	1.00	1.02 E11
7	Buildings	1.48 E13	6.80 E3	1.01 E17	1.00	1.48 E13
8	Geo. Heat Potential	3.32 E15	*		*	

* Transformation ratio for geologic heat not evaluated.

d) The embodied energies were then added to the overview diagram. This provided a perspective on the amount of energy entering the island's subsystems.

e) An aggregated diagram (Figure 3) was produced which reduces the number of systems within the island to a minimum but still retains the essential character of the island and its economy. Several flows were combined (i.e., goods, fuels and fertilizer) and natural energy was restricted to rain energy only. The rationale for this restriction is detailed in Methods section 3.

f) A summary diagram (Figure 4) was then created that combines all high quality inputs and island exports (goods and services) as one. This diagram is the basis for most of the ratios calculated in Methods sections 4 and 5.

3) An energy to dollar ratio was calculated which is based on the total number of calories consumed by the economy divided by the Gross Domestic Product (the total number of dollars flowing through the final demand sector of the economy including exports, government, household consumption, maintenance and growth. An algebraic approach is outlined in the appendix. One drawback to the calculation as defined at this time is that only a rough estimate account is made for the drawdown of island resources if they are occurring, i.e., significant losses of old timber being used for charcoal, soils (in shifting agriculture) or construction that may not have been estimated accurately.

Several natural energy inputs driving the economy are generated simultaneously by global atmospheric and oceanic systems. Energy from rain, wind and beach waves represent different concentrations of original solar energy accumulated primarily over the ocean surface. The procedure for estimating the embodied solar energy of these inputs is to evaluate them separately and then to choose the largest one. This minimizes the possibility of "double counting" the same calories of input.

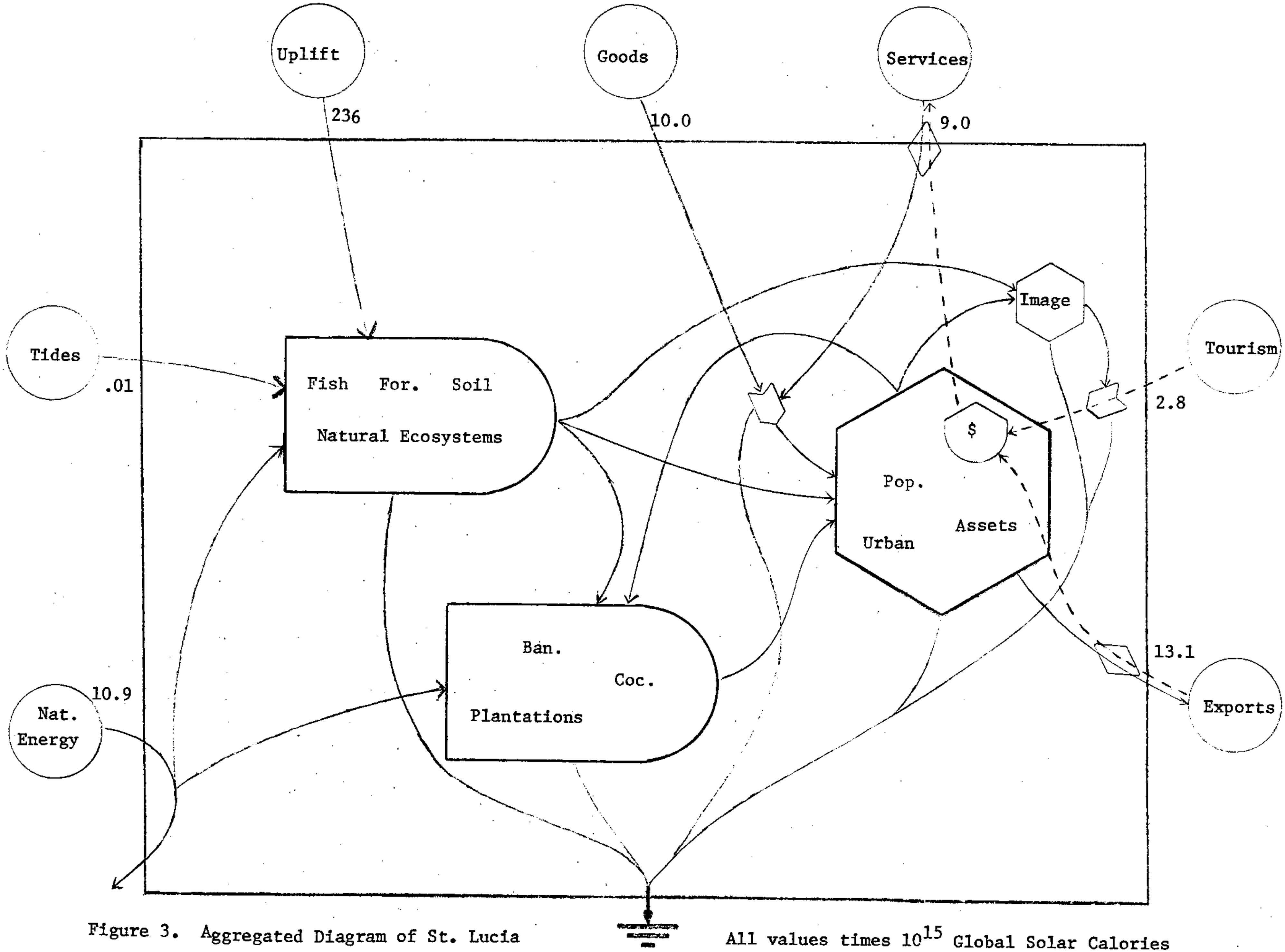


Figure 3. Aggregated Diagram of St. Lucia

All values times 10^{15} Global Solar Calories

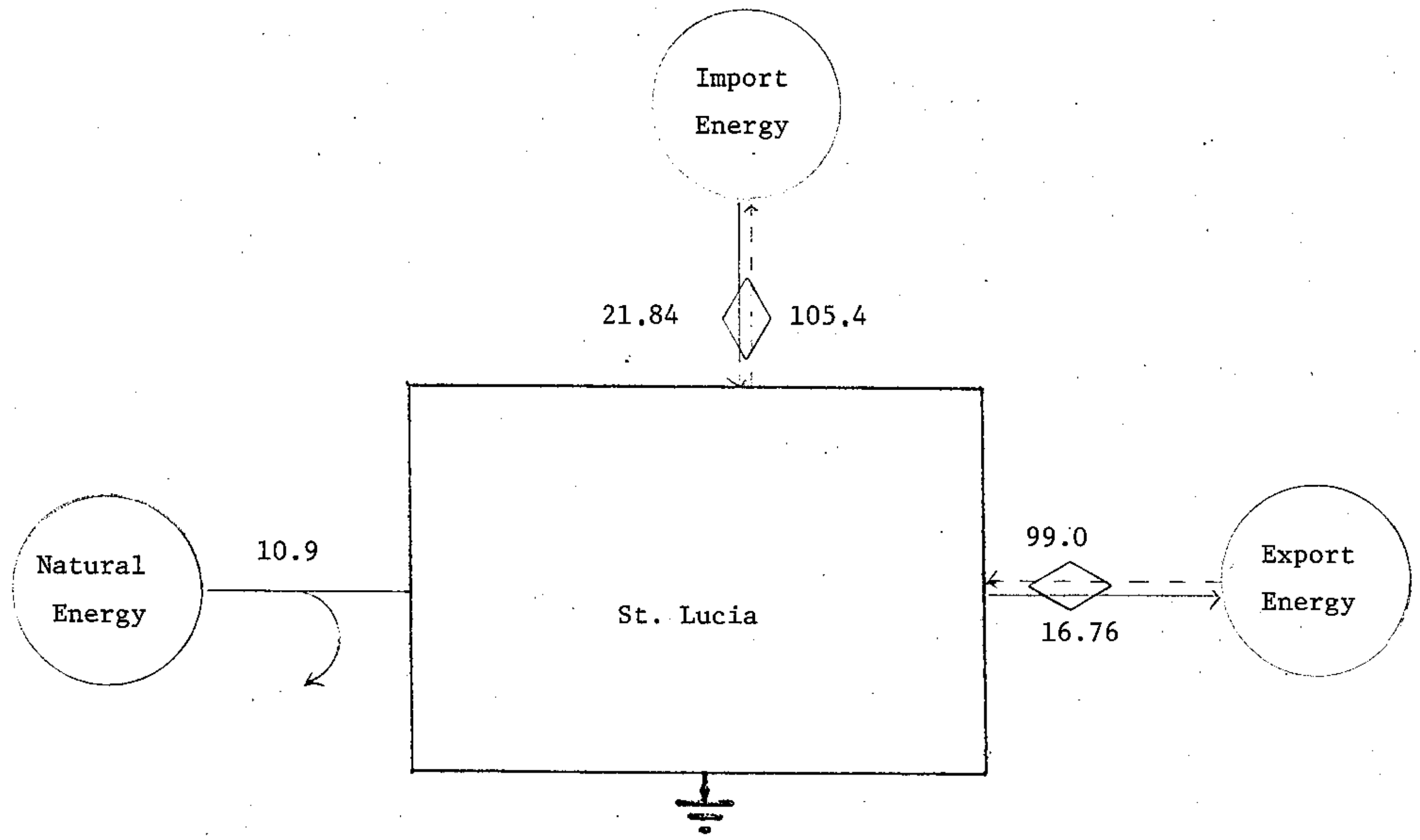


Figure 4. Summary Diagram of St. Lucia. Calorie Values times 10^{15} Global Solar Calories. Dollar values times 10^{6} U.S.

There was some uncertainty about the magnitude of wave energy, derived from trade winds, because (a) a percentage of approaching waves are reflected by rocky headlands and no data was available regarding the extent of shoreline that wave absorbing beaches represent, and (b) the wave heights were measured at sea in the vicinity of the island and may not be the same size near shore.

Similar uncertainties exist for the geologic uplift rate. Rates were taken for the Virgin Islands and Jamaica, neither of which are in the subduction zone that contains St. Lucia. For these reasons the energy to dollar ratio was based solely on the chemical potential of rain. Tidal energies were 3 orders of magnitude smaller than that of rainfall and consequently neglected.

Also, since imports (imported services) were calculated only using solar derived inputs to the economies of the exporting nations, island exports must be handled similarly for consistency of approach.

4) Other useful ratios were calculated based on the natural energy contribution with all flows expressed in equivalent calories of one type.

a) National output to input ratio which is the embodied energy of the island outputs (products, reexports and services, i.e., labor) divided by the sum of all imports (fuel, fertilizer, goods and services). This ratio is analogous to a technical efficiency ratio (output/input).

b) The important matching ratio is equivalent to the embodied energy of imports (higher quality energies) divided by the energies obtained form the environment, i.e., purchased energy per free energy. This ratio is useful in comparisons because it indicates the intensity of fossil fuel energy use and the degree of effective energy matching.

c) The energy added factor is the sum of exported goods and services divided by the sum of the natural energy inputs which indicates how effective the exported resources are in attracting, or demanding, high quality inputs.

d) The net energy calculation is simply imported energies minus exported energies. It is essentially the trade balance.

e) The per capita energy use is the total energy use within the country divided by the population. This is one measure of the standard of living that includes non-monied and economic inputs. The result may be compared with values of 7.94 E 11 GSC for the United States. This measure gives higher estimates of standards of living than where there are subsistence economies.

f) The carrying capacity using solely income in regions without imports may be calculated for a particular standard of living (embodied energy use per person). An estimate was made using the current energy per person.

g) The carrying capacity with competitive imports is the number of people at the defined standard of living that may be supported if embodied energy from outside were sttracted through various sales, services, attractions to equal that of the average developed country. This is a measure of the degree of economic development.

h) The density of energy use is estimated by dividing total energy use by the area of the country including its continental shelves.

A summary of these ratios is given in Table 3.

5) Three subsystems of St. Lucia were examined. Potential for geothermal electrical production was considered along with the tourist industry and banana production. A summary diagram accompanies each analysis along with a table of calculations. Energy analysis ratios were then calculated for each subsystem.

a) Geothermal Potential: At a 9.5% annual growth in electricity demand, which was the figure the government document used, a need of an installed capacity of 100 MW would be required by the year 2010. Gilliland (1975) made the study of the costs of material and energy requirements to construct and maintain such a plant for thirty years. If the diesel plants now operating were permitted to retire, the steam plant could theoretically handle all of the island's demand well into the next century. A summary of energy requirements and yields is shown in Figure 5 for the 100 MW plant.

b) Tourism: The value of tourist dollars was from the World Bank document (1979 figures). Electricity and fuel consumption were given as percentages of total island use in the OAS document (1982). The "Investing of St. Lucia" folder (Caribbean/Central American Action, 1980) stated an average return of 29.3% on investments in all industries in 1979 for the Caribbean in general. The same document listed a volume of 2890 workers in this industry with an average salary of $480/yr. The dollars paid for goods required to run the industry (Figure 6) were calculated by dividing the dollars remaining after paying for domestic labor by 1.293; profits and taxes make up the remainder. The value of goods required was determined by the percentage (11.4) of the GDP of all importing sectors of the economy that tourism represents; services was determined likewise. Taxes are 45% for most corporations.

c) Banana Plantations: Natural contribution to the banana industry was based on a figure of 9% of total lands in plantations from "Investing in St. Lucia" (1982). The chemical potential of rain was used as a measure for consistency with other calculations. Plantations were taken to be the only recipients of fertilizer imports. Some of this material may be diverted to other agricultural uses but no accurate basis existed for rationing it among uses. Fuel was excluded for the reason that the data from Pimentel would suggest that bananas require about 20% of all imported fuels and the OAS report allocated no significant portion of imports for agricultural use. It is assumed then that the harvesting, fertilizing, etc. is all done by hand. Hard goods (machinery and equipment) accounted for about 50.6% of all material imports (dollar value) and the banana plantation contribution to the GDP among other users of these goods was calculated to be 18.7%, implying that plantations use about 9.5% of imported hard goods and the services to deliver them. The same percentage was used to estimate the dollars paid for these goods. Subtracting this value from the dollar value of the exported goods left \$4.24 E6 which was allocated to labor. This figure was then converted to calories at the domestic ratio.

Details and basis for calculations are contained in the appendices, particularly the methods of calculating the values of imports and exports.

RESULTS

The results of the overview energy analysis are given in Figures 2-4 and in Tables 1-3.

a) Figure 2 is the medium complexity diagram of St. Lucia showing major land uses, energy sources and consumer sectors.

b) Figure 3 is an aggregated diagram depicting the dominant energy centers of the island and the relevant energy sources.

c) Figure 4 is a summary diagram showing only low and high quality energy inputs and exported energies.

d) Tables 1 and 2 are the summaries of flows and storages, respectively.

e) Table 3 represents all ratios calculated for the purposes of comparison with other regions and nations.

f) Figures 5-7 summarize the analyses of a proposed geothermal electrical system, the tourist industry and banana plantations. These are followed by the calculations made to determine relevant flows to each subsystem.

Table 3. Ratios useful for overview analysis using energies in Global Solar Calories x 10^{15}/yr.

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1) Total Natural Energy (based on rain potential) = 10.9

2) Total Imported Energies (including fuels, fertilizers, goods and services, and dollars received) = 21.84

3) Total Exports (including goods, export services and tourist services) = 16.76.

- A) Total Energy Inflow = 32.74
  - a1) % energy use from the environment = 33.3%
  - a2) % energy use from all imports = 66.7%
- B) Ratio of exports to imports = 0.767
- C) Total energy consumed within = 15.98
  - c1) Density of energy use = 2.59 E7 GSC/m^2 (2.59 E3 GSC/ha)
  - c2) Per capita energy use = 1.28 E11 GSC/person
- D) Exports minus Imports = 5.08
- E) Imports to Natural Energy Ratio = 2.00
- F) Natural Carrying Capacity (at current standard of living) = 41,582
- G) Developed Carrying Capacity (at an investment of 3 to 1) = 168,330

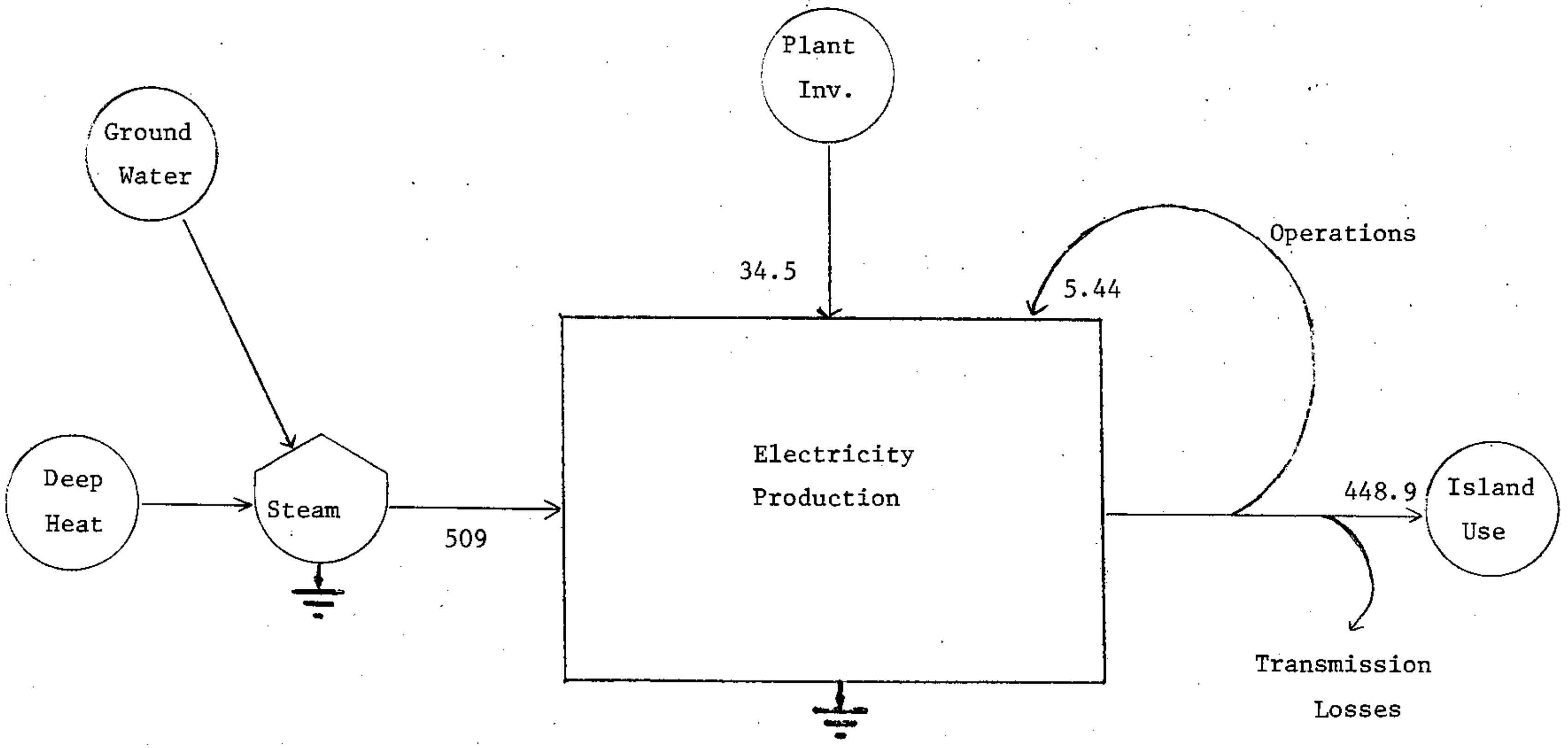

Figure 5. Hypothetical Geothermal Electrical Production. All values times 10^{15} Global Solar Cal. Values are for a dry steam, 100 MW plant with a thirty year lifespan.

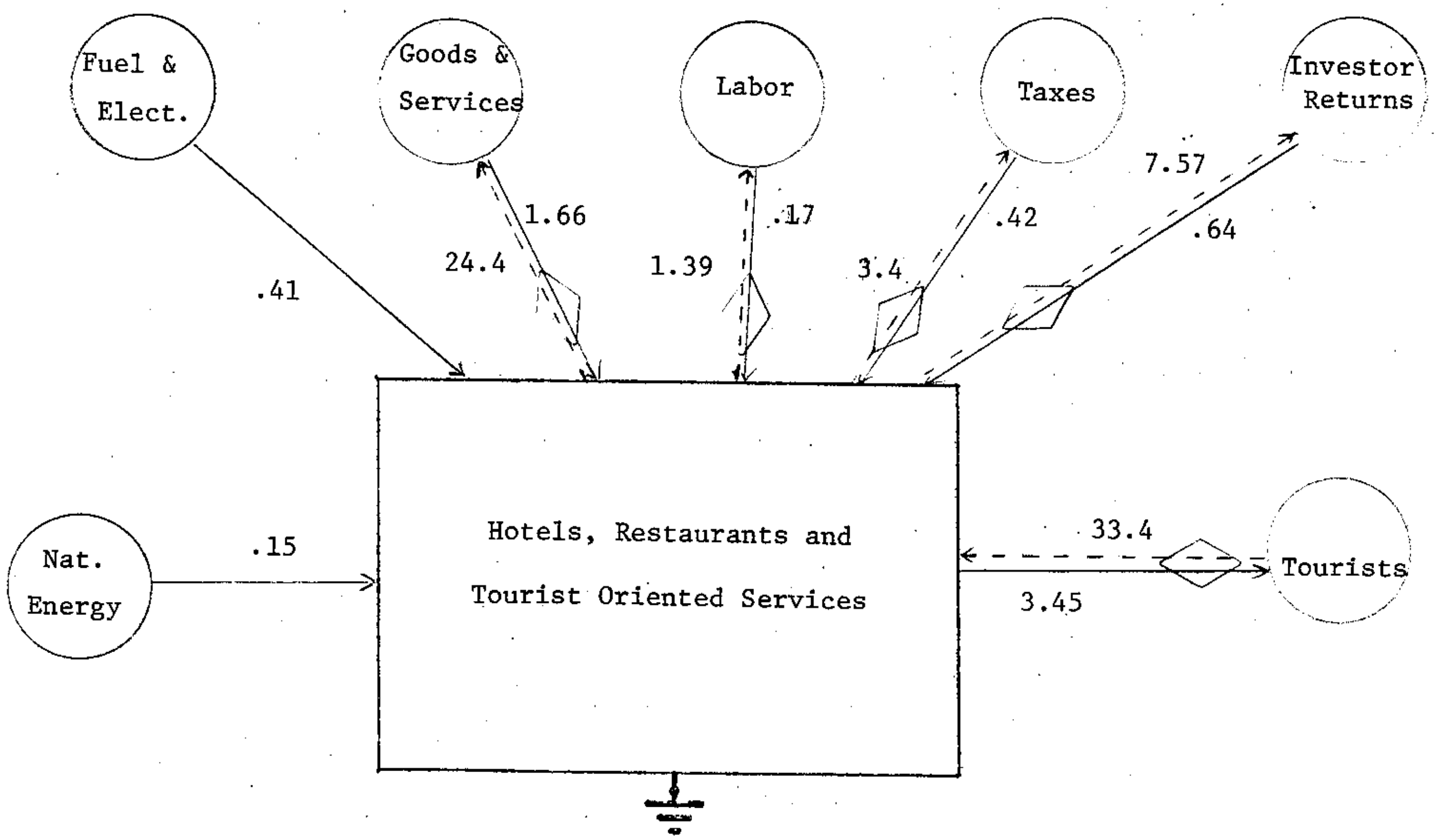

Figure 6. Summary Diagram of the Tourist Industry of St. Lucia.

Dollar values are times 10^6 U.S. Energy values are times 10^{15} GSC.

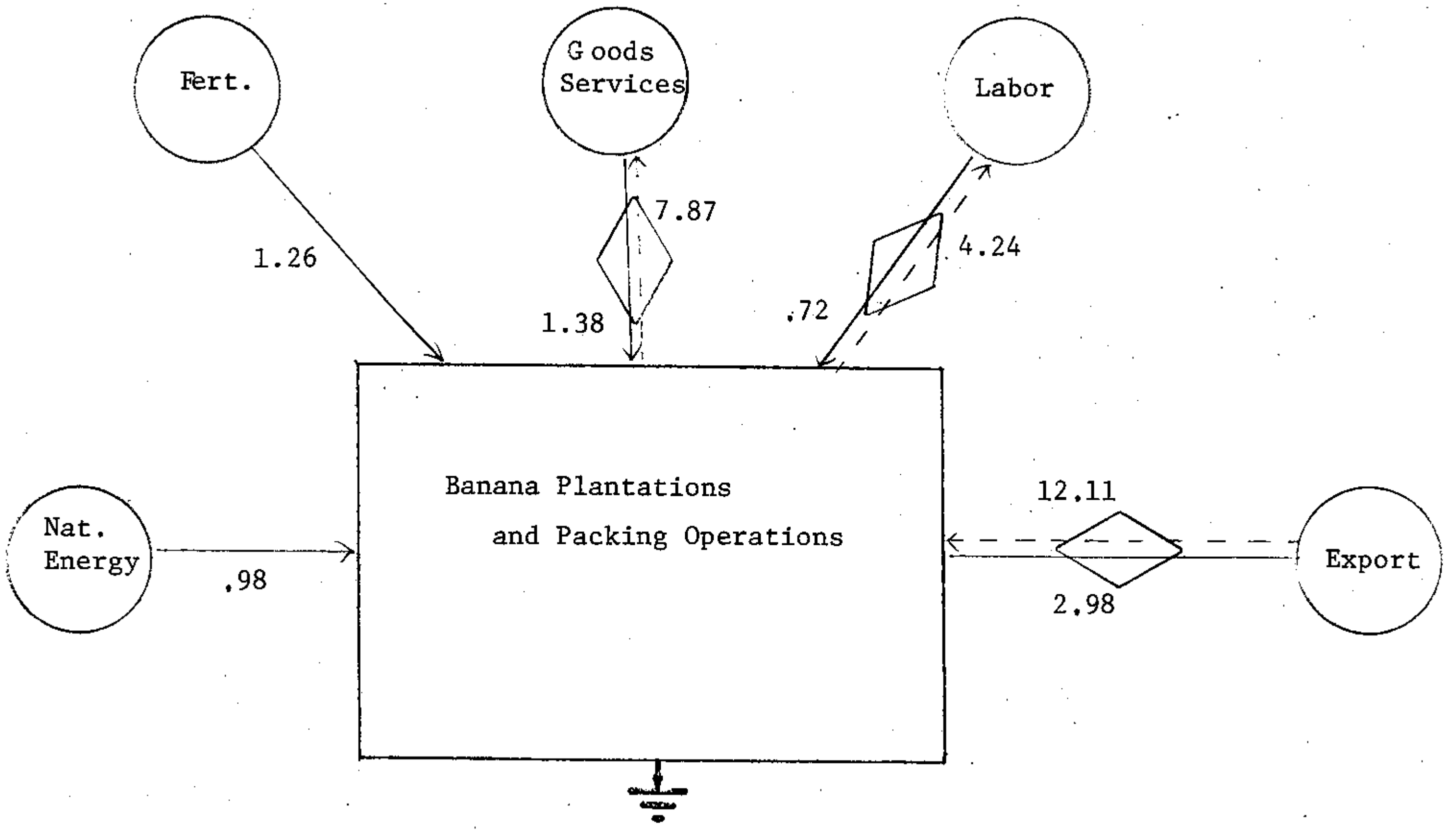

Figure 7. Summary Diagram for the Banana Industry. Calorie values times 10^{15} Global Solar Cal. Dollar values times 10^{6} U.S.

DISCUSSION

Some of the data for natural energy sources needs to be refined, especially wave energy. Uplift, considering its magnitude, should probably be looked at more closely. Where these are reevaluated the calculated natural contributions to St. Lucia's economy are likely to increase. The implications of this would be a higher calorie/dollar ratio and a more competitive position for the island in terms of attracting outside energies.

The effects of hurricanes were not included in the analysis because there is not enough information on the degree of absorption of energy by the island, i.e., how much energy goes into constructive processes versus how much goes into destructive ones. The hurricane pulse occurs about every 9 years.

The flow of deep heat into regions that can be tapped by the economy was unknown, though the storage supplied by it was evaluated.

Feasibility of Further Development

The general level of energy use and the percentage that environmental energies are of the total classify St. Lucia as a developing nation. The ratio of imported energies to the natural contribution is 2.0, which is less than typical developed ratios (2.5-3.5) but higher than the world average of 0.6 (based on total fossil fuel use divided by the solar flux). Presumably this gives St. Lucia a competitive position by offering more real contribution to the economy per unit of investment than developed regions. As St. Lucia attracts more energies, both the standard of living and the population may rise. At current levels of living a population of over 165,000 could be supported.

Of major importance to increasing development is St. Lucia's potential for geothermal power. This large natural source could be matched by additional imports of high quality, excluding fossil fuels. In developed nations electricity often is one-fourth of all energy use while in St. Lucia it is less than 8%. According to the estimates of geological heat storages, an increase in power demand of this site is feasible.

A shift towards higher quality infrastructure, hotels, education and cultural centers would attract more high quality goods and consumer dollars. Such a shift is possible if more use is made of St. Lucia's natural endowment of resources. The Aquater Study (1982) predicted savings in the range of $17 million dollars a year using a small (20 MW) plant. These dollars could be used to improve credit status, pay for higher quality gear for fishing, tourist advertising or cultural benefits for the island population.

Geothermal Potential

As noted above, geothermal production of power for St. Lucia could be strongly beneficial. Based on estimates of heat storage there is sufficient energy to run a 100 MW plant for 300 years and this does not include the addition of new energies from below over time. Compared with the average effect of fossil fuel purchases (6 units of energy imported for 1 unit exported) geothermal has twice the yield per unit of investment. It should be noted, however, that centralization of power sources does have the problem of increased vulnerability, i.e., hurricane effects, and smaller plants may still be useful in more isolated areas.

Tourism

With an investment ratio of about 22, the tourist industry is 10-11 times as intense as the general economy in the use of purchased energies. At the same time its yield ratio (assuming that tourist services are equivalent to all inputs to the industry) is about 0.82, which is 7% higher than the island average.

As long as the industry is profitable it will continue to attract additional investment up to the point where the density of tourist centers has a negative effect on "image." Policies should be directed towards maximizing image by restricting density and maintaining environmental quality. While manufacturing (not evaluated) is apparently receiving the benefit of most of the current development policies, tourism can still be developed further.

Pollution effects were not considered for lack of data. Further consideration for development of the tourist industry should account for the costs of increases in wastes (sewage, smoke from diesel plants, and fumes from taxis and jets).

Plantations

The investment ratio for bananas was 3.4, higher than the island average. A significant fraction of invested energies was in the form of fertilizers, while labor was a smaller percentage.

Two means of evaluating embodied energy were compared; one based on a fossil fuel input over less land while the other was based on land area only. The results were within 6% of each other, indicating fertilizer and land are, at this level of use, fairly interchangeable. A decrease in fertilizer use would probably require an attendant increase in labor, with total investment in embodied energy remaining fairly constant.

The yield ratio (0.84) is higher than the island average, indicating that plantations are circulating more high quality energy into the enviornment than some other sectors of the economy.

APPENDICES

APPENDIX A

Calculations for Table 1: Dominant Flows Across the St. Lucia Boundary

1. Solar influx:

   $(180\ \mathrm{Cal/cm^2 \cdot yr})(1\ \mathrm{E4\ cm^2/m^2}) = 1.8\ \mathrm{E6\ Cal/m^2 \cdot yr}$

   $(1.8\ \mathrm{E6\ Cal/m^2 \cdot yr})(6.16\ \mathrm{E8\ m^2}) = 1.11\ \mathrm{E15\ Cal/yr}$

   Insolation rate from Budyko, <u>Climate and Life</u>, 1974

   Area of St. Lucia from the <u>National Basic Intelligence Factbook</u>, CIA, 1977

2. Chemical Potential of Rain:

   $F_r = PC_2(nRT)\ln(C_2/C_1)$

   $= PC_2(1.987\ \mathrm{E{-}3\ Cal/°K\ mole})(301°\mathrm{K})\ln(999990/965000)/(18\ \mathrm{g/mole})$

   $= PC_2(1.18\ \mathrm{E{-}3\ Cal/g})$

   $= (2.17\ \mathrm{m/yr})(999990\ \mathrm{g/m^3})(1.18\ \mathrm{E{-}3\ Cal/g}) = 2.56\ \mathrm{E3\ Cal/m^2 \cdot yr}$

   $(2.56\ \mathrm{E3\ Cal/m^2 .yr})(6.16\ \mathrm{E8\ m^2}) = 1.58\ \mathrm{E12\ Cal/yr}$

   Average yearly temperature is 28°C, from <u>Investing in St. Lucia</u>, Caribbean/Central Americal Action, 1982.

   Average rainfall determined by isohyetal method using data from the <u>Preliminary Data Atlas (St. Lucia)</u>, Caribbean Conservation Association, 1980.

3. Kinetic Potential of Rain:

   $K_e = P(1/2)(MV^2)(2.38\ \mathrm{E{-}11\ Cal/erg})$

   $= P(1/2)(1\ \mathrm{g/cm^3})(762\ \mathrm{cm/sec})^2(2.38\ \mathrm{E{-}11\ Cal/erg})$

   $= P(6.91\ \mathrm{E{-}6\ Cal/cm^3})$

   $= (217\ \mathrm{cm/yr})(1\ \mathrm{E4\ cm^2/m^2})(6.91\ \mathrm{E{-}6\ Cal/cm^3}) = 1.50\ \mathrm{E1\ Cal/m^2 \cdot yr}$

   $(1.50\ \mathrm{E1\ Cal/m^2 \cdot yr})(6.16\ \mathrm{E8\ m^2}) = 9.24\ \mathrm{E9\ Cal/yr}$

   Kinetic energy of $6.91\ \mathrm{E{-}6\ Cal/cm^3}$ is based on an average raindrop diameter of 4 mm and an average falling velocity of 762 cm/sec from Todd, <u>The Water Encyclopedia</u>, 1970.

4. Wind:

$$P_m = Z_b p K_m (du/dz)^2 (7534\ \text{Cal/watt})$$

$$= (1\ \text{E}\ 3\text{m})(1.23\ \text{kg/m}^3)(4.5\ \text{m}^2\text{/sec})(3.2\ \text{E-3/sec})^2(7534\ \text{Cal/watt})$$

$$= 4.27\ \text{E}\ 2\ \text{Cal/m}^2$$

$$(4.27\ \text{E}\ 2\ \text{Cal/m}^2)(6.16\ \text{E}\ 8\ \text{m}^2) = 2.63\ \text{E}\ 11\ \text{Cal}$$

Average boundary layer taken as 1 E3 m over open water and eddy diffusion coefficient taken as the yearly average from charts in The General Circulation of the Tropical Atmosphere, Vol. 1, Newell, et al., 1972.

Vertical wind gradient based on average wind speed at surface of 2.8 m/sec and at 1 E 3 m of 6 m/sec also from Newell, et al.

5. Runoff:

Calculation based on the gravitational potential of average rainfall.

$$G_e = P(pgh)(2.38\ \text{E-11}\ \text{Cal/erg})$$

$$= P(1\ \text{g/cm}^3)(980\ \text{cm/sec}^2)(2.64\ \text{E}\ 4\ \text{cm})(2.38\ \text{E-11}\ \text{Cal/erg})$$

$$= P(6.11\ \text{E-4}\ \text{Cal/cm}^3)$$

$$= (217\ \text{cm/yr})(1\ \text{E}\ 4\ \text{cm}^2\text{/m}^2)(6.11\ \text{E-4}\ \text{Cal/cm}^3) = 1.33\ \text{E}\ 3\ \text{Cal/m}^2\text{yr}$$

$$(1.33\ \text{E}\ 3\ \text{Cal/m}^2\cdot\text{yr})(6.16\ \text{E}\ 8\ \text{m}^2) = 8.17\ \text{E}\ 11\ \text{Cal/yr}$$

$$(8.17\ \text{E}\ 11\ \text{Cal/yr})(.39) = 4.98\ \text{E}\ 11\ \text{Cal/yr}$$

Average height of St. Lucia measured to be 860 ft. (2.62 E 4 cm) by isoplethal method using data from the Preliminary Data Atlas (St. Lucia), Caribbean Conservation Association, 1980.

Runoff rate is 39% from Odum, A Tropical Rain Forest, 1970.

6. Waves:

$E_W = (1/8)\rho g h^2 C(2.38\ E\text{-}11\ Cal/erg)$

$= (1/8)(1.025\ g/cm^3)(980\ cm/sec^2)(122\ cm)^2 \cdot C \cdot (2.38\ E\text{-}11\ Cal/erg)$

$= (4.448\ E\text{-}5\ Cal/cm^2) \cdot C$

$= (4.45\ E\text{-}1\ Cal/m^2) \cdot C$

$C = [(9.8\ m/sec^2)(5m)]^{1/2}(3.15\ E\ 7\ sec/yr) = 2.205\ E\ 8\ m/yr$

$E_W = (4.448\ E\text{-}1\ Cal/m^2)(2.205\ E\ 8\ m/yr) = 9.81\ E\ 7\ Cal/m \cdot yr$

$(9.81\ E7\ Cal/m \cdot yr)(4.089\ m) = 4.01\ E\ 12\ Cal/yr$

Shoaling depth taken as 5 meters.

Average wave height is 4 ft (14 cm) from Table 19 ,

Synoptic Meteorological Observations, U.S. Naval Weather Service Command

Shore length measured to be 25.4 m; (40.9 km) based on typical wave direction (ENE).

7. Tides:

$E_t = (.5)NA(.5)\rho g h^2(2.38\ E\text{-}11\ Cal/erg)$

$= (.5)(\ 365\ Tide/yr)(5.95\ E\ 11\ cm^2)(.5)(1.025\ g/cm^3)(980\ cm/sec^2)$

$(2.74\ E\ 1\ cm)^2(2.38\ E\text{-}11\ Cal/erg)$

$= 9.74\ E\ 8\ Cal/yr$

Mean tidal height (diurnal) = .9 ft = 2.74 E 1 cm. Source is NOS Tidal Tables through the NOAA Office of Tidal Predictions.

Tidal shelf measured to be 5.95 E 7 m^2 to a depth of 18.3 m (10 fathoms).

8. Uplift:

E_u = (pghd)(2.38 E-11 Cal/erg)

= 3.0 g/cm^3)(980 cm/sec^2)(.015 cm/yr)(.0075 cm)(2.38 E-11 Cal/erg)

= 7.87 E-12 Cal/cm^2·yr

(7.87 E-12 Cal/cm^{2}yr)(1 E4 cm^2/m^2)(6.16 E 8 m^2) = 4.85 E 1 Cal/yr

Average weight of representative igneous rocks is 3.0 g/cm^3 from Stratham, Earth Surface Sediment Transport, 1977. Uplift rate determined by the average of values from Horsfield, Late Tertiary and Quaternary Crustal Movements in Jamaica, 1973 (.02 cm/yr) and from Whetten, Geology of St. Croix, U.S. Virgin Islands, 1962 (.01 cm/yr).

9. Chemical Potential of Uplifted Land:

E_u = phG(1 E 4)

= (3.0 g/cm^3)(.015 cm/yr)(.041 Cal/g)(1 E 4 cm^2/m^2)

= 1.85 E 1 Cal/m^2·yr

(1.85 E 1 Cal/m^2·yr)(6.16 E 8 m^2) = 1.14 E 10 Cal/yr

Density of rocks is from Statham, 1977 for basalt. Island substrate is andesitic basalt from Exploration of St. Lucia's Geothermal Resources, Gov't of St. Lucia, 1982.

Heat content for rock from Gilliland, 1978.

Rate of uplift - see Ref. Number 8.

10. Fuel:

(.044 E 6 MTCE)(7 E 6 Cal/MTCE) = 3.08 E 11 Cal

Data from World Energy Supplies, U.N., 1979, (1978 figures)

(220926 BOE)(5.8 E 6 BTU/BOE)(.252 Cal/BTU) = 3.24 E 11 Cal

Data from First Workshop on OAS Regional Human Settlements and Energy Project, 1982, Workshop Conclusions and Project Proposals, (1980 figures)

1979 Rate of fuel consumption taken as the average of 1978 and 1980:

(3.08 + 3.24)/2 = 3.16 E 11 Cal/yr

11. Fertilizer (nitrogen):

(2.04 E 3 Joules/g)(.2389 Cal/Joule)(1 E-3 Cal/cal) = 4.87 E-1 Cal/g

(4.87 E-1 Cal/g)(2 E 3 Met. Ton)(1 E 6 g/MT) = 9.75 E 8 Cal

Gibbs Free Energy value from Anderson, J.W., Bioenergetics of Autotrophs and Heterotrophs, 1980. Energy Transformation Ratio from H.T. Odum based on fuel requirements for manufacture from Mohinder, S., Energy and Fertilizer, Policy Issues and Options for Developing Countries, 1982, and costs of services based on 1980 U.S. prices ($128/ton).

12. Fertilizer (phosphate):

(.382 Cal/g)(1400 Met. Ton)(1 E 6 g/MT) = 5.36 E 8 Cal

Energy value of phosphate concentrate from Energy System of New Zealand, Odum and Odum, 1980.

Consumption of both nitrogenous and phosphate fertilizers from FAO Fertilizer Yearbook, U.N., 1978.

13. Imports to St. Lucia

Table 4. Weight and Calorie values of major imports (excluding fuel and fertilizer).

Item	Quantity 1 E3 kg (1)	Actual Calories 1 E3 Cal/kg (2)	GSC Natural 1 E6 Cal/kg (3)	GSC Fos. Fuel 1 E6 Cal/kg (4)	GSC Total (3+4) 1 E5 Cal/kg (5)	GSC Labor ($) 1 E8 Cal/kg (6)	GSC Total (5x1) 1 E14 Cal/kg (7)	ETR (5+6)/2 (8)
Meats	4207	2.76	97.55	2.92	10.05	1.01	4.23	7.30 E4
Sugar	2105	4.25	6.56	8.75	1.53	.73	.32	2.08 E4
Fruit, Vegetables	2152	.30	.86	12.50	1.34	.66	.29	2.65 E5
Grain	12728	3.33	5.14	11.62	1.68	.26	2.13	1.29 E4
Lumber	6089	3.30	9.54	20.44	3.00	.26	1.83	1.70 E4
Paper	13660	4.20	55.08	4.92	6.00	.31	8.20	1.50 E4
Cement	20469	.044	8.77	14.63	2.34	.08	4.79	7.14 E5
Glass	8122	4.18	27.69	39.81	6.75	.20	5.48	2.09 E4
Steel	7192	1.54	140.07	39.82	17.99	.15	12.94	1.27 E5
Non-elect. Machinery	7011	1.54	140.07	39.82	17.99[a]	1.45	12.61	2.11 E5
Electrical Machinery	506	1.54	140.07	39.82	17.99[a]	5.82	.91	4.95 E5
Transportation	1912	1.54	140.07	39.82	17.99[a]	2.70	3.44	2.92 E5
Textiles	425	3.31	45.58	59.32	10.49	6.89	.45	2.40 E5
Evap. Cond. Milk	1560	6.50	22.10	25.43	4.75	1.16	.74	2.52 E4
Non-fertilizer Chems.	4798	12.20	140.15	7.87	14.80	1.06	7.10	2.08 E4
Misc. Mfg. Goods	950	4.83	22.92	25.14	4.81	6.07	.46	1.36 E5
Plastic	626	6.61	1.5	28.50	3.00	1.74	.18	3.09 E4
						Total	66.10 E14	

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[a] Fossil fuel and embodied energies should be higher than this figure.

14. Imported Services:

Calculation based on Calorie/$ ratios of the following dominant trading nations:

U.S. = 37%

U.K. = 19.4%

Developed nations (exc. US, UK) = 17%

Trinidad = 9.7%

Developing nations (exc. Trinidad) = 16.5%

Centrally planned economies excluded.

U.S.: GDP = ($10630/person)(223.6 E6 persons) = $2.38 E12

Natural energy = 6.74 E 15 Cal CE

Fuel consumption = (12350 kg CE/person)(2.23.6 E6 persons)(7 E3 Cal CE/kg CE)
= 1.93 E 16 Cal CE/yr

Total Energy = 2.61 E 16 Cal CE/yr

2.61 E 16 Cal CE/$2.38 E12 = 1.097 E4 Cal CE/$

U.K.: GDP = ($6320/person)(55.9 E6 persons) = $3.53 E11

Natural energy = (90 Cal/cm^2/yr)(1 E4 cm^2/m^2)(245 E9 m^2) = 2.205 E17 Cal/yr
= 1.10 E14 Cal CE

Fuel consumption = (5637 kg CE/person)(55.9 E6 persons)(7 E3 Cal CE/kg CE
= 2.21 E15 Cal CE/yr

Total Energy = 2.32 E15 Cal CE/yr

2.32 E 15 Cal CE/$3.53 E11 = 6.572 E3 Cal CE/$

Developed Nations (excl. US, UK):

GDP = ($9561/person)(391.7 E6 persons) = $3.745 E12

National energy = (110 Cal/cm^2)(1 E4 cm^2/m^2)(20822 E9 m^2) = 2.29 E 19 Cal
= 1.145 E 16 Cal CE

Fuel consumption = (7754.3 kg CE/person)(391.7 E6 persons)(7 E3 Cal CE/kg CE
= 2.126 E 16 Cal CE/yr

Total energy = 3.271 E 16 Cal CE/yr

3.271 E 16 Cal CE/$3.745 E 12 = 8.735 E3 Cal CE/$

Trinidad: GDP = (\$3390/person)(1.2 E6 persons) = \$4.068 E9

National energy = (180 Cal/cm^2·yr)(1 E4 cm^2/m^2)(5 E9 m^2) = 9 E15 Cal/yr
= 4.5 E12 Cal CE/yr

Fuel consumption = (5037 kg CE/person·yr)(1.2 E6 persons)(7 E3 Cal CE/kg CE)

= 4.23 E 13 Cal CE/yr

Total energy = 4.68 E 13 Cal CE/yr

4.68 E 13 Cal CE/\$4.068 E9 = 1.151 E4 Cal CE/\$

Developing Nations: GDP = (\$1387/person)(983.8 E6 persons) = \$1.365 E 12

Natural energy = (150 Cal/cm^2·yr)(1 E4 cm^2/m^2)(38700 E9 m^2) = 5.805 E19 Cal/yr

≒ 2.90 E 16 Cal CE/yr

Fuel consumption = (1160.4 kg CE/person)(983.8 E6 persons)(7 E3 Cal CE/kg CE)

= 7.99 E 15 Cal CE/yr

Total energy = 3.70 E 16 Cal CE/yr

3.70 E 16 Cal CE/\$1.365 E 12 = 2.71 E4 Cal CE/\$

Weighted Average = (.37)(1.097 E4) = 4.059 E3

(.194)(6572) = 1.275 E3

(.17)(8735) = 1.485 E3

(.097)(11510) = 1.116 E3

(.165)(27100) = $\underline{\text{4.472 E3}}$

= 1.2407 E4 Cal CE/\$

= 8.437 E7 GSC/\$

Subtracting the costs of fuel (15) and fertilizer (16) from the total (\$105.4 E6: World Bank Economic Memorandum on St. Lucia, 1982) yields \$94.35 E6

(\$94.35 E6)(1.2407 E4 Cal CE/\$)(6800 GSC/Cal CE) = 7.96 E 15 Cal

Data on GDP, population, area, and fuel consumption from World Development Report, World Bank, 1981.

Solar insolation was used as the basis for the natural energy contribution. Insolation values (natural energy) from Budyko, Climate and Life, 1974.

15. Cost of Fuel:

(8.437 E7 Cal/$)($10 E6) = 8.437 E 14 Cal

Dollar value from World Bank Economic Memorandum.

16. Cost of Fertilizer:

(8.437 E7 Cal/$)($1.054 E6) = 8.89 E 13 Cal

Based on 1978 dollar value as a percent of all chemical imports (12.25%)

Using a constant percentage: (.1225)($8.6 E6) = $1.054 E6

Data from 1980 Yearbook of International Trade Statistics, U.N., 1981.

17. Exports from St. Lucia

Table 5. Weight and Calorie values of major exports.

Item	Quantity 1 E3 kg (1)	Actual Calories 1 E3 Cal/ kg (2)	GSC Natural 1 E6 Cal/ kg (3)	GSC Fos. Fuel 1 E6 Cal/ kg (4)	GSC Total (3+4) 1 E7 Cal/ kg (5)	GSC Labor ($) 1 E8 Cal/ kg (6)	GSC Total (1x5) 1 E14 Cal (7)	ETR (5+6)/2 (8)
Bananas	48986	.693	9.30	9.52	1.88	.42	9.22	8.82 E4
Paper Products	5141	4.20	10.0	50.00	6.00	.95	3.08	3.70 E4
Coconut Oil	2656	8.82	120.70		(12.07)	1.28	(3.21)	2.82 E4
Wastepaper Pulp	1326	4.20	10.0	2.94	1.29	.23	.17	8.55 E3
Veg. Oil Residues	1235	8.82	120.70		(12.07)	.18	(1.49)	1.57 E4
Nuts	919		33.50		(3.35)	.24	(.31)	
Fodder	863		12.37	3.20	1.56	.39	.13	
Fruits	787		33.50		(3.35)	.28	(.26)	
Soap	130	8.82	120.70	.434	12.11	1.11	.16	2.64 E4
Clothes	160	3.31				23.80		(7.19 E5)
Chemicals	392	12.20	140.15	7.87	14.80	.60	.58	1.70 E4
Vegetables	353	.30	12.02	7.63	1.97	.51	.07	2.35 E5
Bran	1387					.20		
Spices	331		33.50		(3.35)	2.87	(.11)	

Total embodied energy of exports
excluding labor = 18.79

Effort made to include items of economic value and items that represent the material bulk of exports in general.

Blanks reflect lack of available data. Figures in parentheses represent approximate value.

18. Electricity:

(.05 E 9 KWH)(8.6 E 2 Cal/KWH) = 4.3 E 10 Cal

Data from World Energy Supplies, U.N., 1979. (1978 figures)

(63.079 MWH)(8.6 E 5 Cal/MWH) = 5.42 E 10 Cal

Data from Workshop Conclusions and Project Proposals, OAS, 1982, (1980 figures).

1979 taken to be the average of these two levels of consumption.

(4.3 + 5.42)/2 = 4.86 E 10 Cal

19. Exported Services:

Based on 1.703 E8 GSC/$ (see calculations - Section III)

(1.703 E8 GSC/$)($65.59 E6) = 1.12 E 16 GSC

20. Tourism:

($33.4 E6)(8.437 E7 GSC/$) = 2.82 E15

Value of tourist expenditures is from Economic Memorandum on St. Lucia, World Bank, 1981.

Cal/$ ratio for imports was used since tourists do not remove energy from the island directly and dollars received are used primarily to pay for imports.

* Hurricanes:

$(4.85 \text{ E } 5 \text{ Cal/m}^2\cdot\text{day})(.03)(.1) = 1.455 \text{ E } 3 \text{ Cal/m}^2\cdot\text{day}$

$(1.455 \text{ E } 3 \text{ Cal/m}^2\cdot\text{day})(6.16 \text{ E } 8 \text{ m}^2\cdot\text{day}) = 8.96 \text{ E } 11 \text{ Cal}$ (per hurricane)

Average energy of a hurricane from "On the low-level wind structure of tropical storms," Hughes (Journal of Meteorology 9:422-28). 3% of total hurricane energy is kinetic and 10% of the kinetic energy is delivered to the surface through friction, from Riehl, Climate and Weather in the Tropics, 1979.

Energy Transformation Ratio from H.T. Odum based on average number of tropical storms and the 3% conversion factor for destructive wind energy.

APPENDIX B

Calculations for Table 2: Dominant Storages Within St. Lucia

(1) Soil:

E_S = KRBD

= (5.4 Cal/g O.M.)(5.69 E3 g O.M./g T.M.)(1.47 E6 g T.M./m^3)(.18 m^2)

= 8.13 E3 Cal/m^2

(8.13 E3 Cal/m^2)(6.16 E8 m^2) = 5.01 E12 Cal

K is empirical ratio of organic to total mass from Odum et al., 1981. using similarity of Antilles soils to southeast U.S. where "red-yellow" soils are predominant. Soil type from Mason, "The Ecological Significance of Soil Shrinkage," 1922.

Average soil density from Odum et al., 1981.

Average soil depth based on similarity to Dominica from Odum, A Tropical Rain Forest.

(2) Chemical Potential in Base Rocks:

E_r = phG

= (3.0 g/cm^3)(.041 Cal/g)(2.62 E4 cm)(1 E4 cm^2/m^2)

= 3.22 E7 Cal/m^2

(3.22 E7 Cal/m^2)(6.16 E8 m^2) = 1.99 E16 Cal

Average density of Basaltic rock from Stratham, 1977

Energy per gram from Gilliland, 1976

Height: see Flow 5 (taken as island height above sea level)

(3) Potential in Uplifted Land:

E_1 = pg(.5)h^2(2.38 E11 Cal/erg)

= (.5)(2.6 g/cm^3)(980 cm/sec^2)$(2.62 \text{ E4 cm})^2$(2.38 E11 Cal/erg)

= 2.40 E1 Cal/cm^2

= (2.40 E1 Cal/cm^2)(1 E4 cm^2/m^2) = 2.08 E5 Cal/m^2

(2.40 E5 Cal/m^2)(6.16 E8 m^2) = 1.48 E14 Cal

Density of Basalt rock from Stratham, 1977

Height from Flow 5.

(4) Biomass: based on 1978 land use maps from Preliminary Data Atlas

(1) Natural Lands	Area (m^2)	Ave. Biomass (kg/m^2)	Total g	Cal/g	Cals
Rain Forest	9.71 E7	45	4.37 E12	4.1	1.79 E13
Seasonal Forest	2.70 E7	35	9.45 E11	4.2	3.97 E12
Wood-Scrub Land	3.42 E7	6	2.05 E11	4.6	9.43 E11
				Total	2.28 E13

(2.28 E13 Cal)(2890 GSC/Cal) = 6.59 E16 GSC

(2) Grazing Lands					
Woodland Area	9.69 E7	6	4.85 E11	4.6	2.23 E12
Scrub Areas	7.15 E6	.7	5.01 E9	4.9	2.45 E10
				Total	2.25 E12

(2.25 E12 Cal)(2890 GSC/Cal) = 6.52 E15 GSC

(3) Agricultural Lands					
Annual Crops	1.89 E8	1	1.89 E11	4.5	8.51 E11
Trees	4.87 E7	12	5.84 E11	4.2	2.45 E12
				Total	3.30 E12

(3.30 E12 Cal)(2890 GSC/Cal) = 9.54 E15

Total Biomass = 8.19 E16 GSC 2.84 E13 Cal

Cal/g of tissue type from Lieth and Box, 1972,

Evapotransporation and Primary Productivity

C.W. Thornwrith Memorial Model.

Areas measured using Preliminary Data Analysis maps.

kg/m^2 from Lieth and Whittaker, Communities and Ecosystems.

Annual Crops - mean cultivated land value

Tree Crops - maximum cultivated land value

Scrub-Grazing - mean semidesert scrub value

Woodland - mean woodland/shrubland value

(5) Electrical Structure:

($1.60 E7)(1.2407 E4 Cal CE) = 1.99 E11 Cal CE

Costs based on installed capacity of 16 MW with an investment and depreciation value of $1000/KW. Data from Exploration of St. Lucia's Geothermal Resources, 1982, Gov't of St. Lucia.

Embodied energy does not include calorie content of materials.

(6) Roads:

Paved: Using an average width of 10.6 ft (Dominica)

(270 mi)(5280 ft/mi)(10.6 ft) = 1.51 E7 ft^2

Asphalt: (1.51 E7 ft^2)(15 lb/ft^2)(3 E3 CE Cal/lb) = 6.80 E11 Cal CE

Base: (1.51 E7 ft^2)(54 lb/ft^2)(30 Cal CE/lb) = 2.45 E10 Cal CE

Labor: (1.51 E7 ft^2)($8/yd^2)(1 yd^2/9 ft^2)(19.6 E3 CE Cal/$) = 2.63 E11 Cal CE

Total 9.68 E11 Cal CE

Cost for labor is in 1973 US $ and Cal/$ ratio

Weight per area and calorie content from Brown, 1980, p. 314

Improved: Using an average width of 12.0 ft (Dominica)

(180 mi)(5280 ft/mi)(12.0 ft) = 1.14 E7 ft^2

Base:(1.14 E7 ft^2)(54 lb/ft^2)(30 Cal CE/lb) = 2.08 E10 Cal CE

Labor: (1.14 E7 ft^2)($2/yd^2)(1 yd^2/9 ft^2)(19.6 E3 CE Cal/$) = 4.97 E10 Cal CE

Total = 7.05 E10 Cal CE

Labor for grading taken as 25% of all work done based on number of tractor passes made.

Runway: Using a width of 149 ft (Dominica)

(14,700 ft)(149 ft) = 2.19 E6 ft^2

Base: (2.19 E6 ft^2)(54 lb/ft^2)(30 Cal CE/lb) = 3.55 E9 Cal CE

Asphalt: (2.19 E6 ft^2)(15 lb/ft^2)(3 E3 Cal CE/lb) = 9.86 E10 Cal CE

Total = 1.02 E11 Cal CE

Total for all surfaces = 1.44 E12 Cal CE

Runway length from "Investing in St. Lucia"

(7) Buildings:

Total urban/suburban land is 1.16 E8 m^2 (18.8% of total area)

Commercial/Industrial land is 9.9 E6 m^2 (2.45 E3 acres)

Average 2 story Central Business District has 2.8 E9 Cal CE/acre

(2.8 E9 Cal CE/acre)(2.45 E3 acres) ≃ 6.85 E12 Cal CE

Moderate Density Suburban land is 2.34 E7 m^2 (5.78 E3 acres)

Average Medium Density Residential land has .6 E9 Cal CE/acre

(.6 E9 Cal CE/acre)(5.78 E3 acres) ≃ 3.47 E12 Cal CE

Low Density land is 8.27 E7 m^2(2.04 E4 acres)

Using the following material weight per acre:

Wood 130 E3 lb (1500 Cal/lb) = 1.95 E8

Organic 16 E3 lb (1500 Cal/lb) = 2.4 E7

Metal 2 E3 lb (700 Cal/lb) ≃ 1.4 E6

Total = 2.2 E8 Cal CE/acre

(2.2 E8 Cal CE/acre)(2.04 E4 acres) = 4.50 E12 Cal CE

Total Building Calories = 1.48 E13 Cal CE

Calorie value of land use from Brown, 1980,

(8) Geological Heat Potential:

From "Exploration of St. Lucia, Geothermal Resource"

There is an estimate of a heated chamber 1000 m thick and approximately 2.16 E7 m^2 in area containing brine water at between 200 and 250°C

(2.16 E10 m^3)(1 E2 cm/m)^3(1.025 g/cm^3) = 2.21 E16 g

(2.21 E16 g)(1 E3 Cal/g°K)(523°K) = 1.58 E16 Cal

Actual heat potential is based on Carnot efficiency:

(1.58 E16 Cal)(523° − 373°)/523° = 3.32 E15 Cal

where $\Delta T°$ is the difference between superheated water and condensed steam (i.e. where steam can no longer be generated).

Only 50% of this figure can be used to yield maximum power:

(3.32 E15 Cal)(.5) = 1.66 E15 Cal

APPENDIX C

Footnotes to Table 4: Imports to St. Lucia, including calculations of energy values.

Notes to Table 4

(1) All values are from the 1980 Yearbook of Interantional Trade Statistics, U.N., 1981.

(2) Actual (Chamical Potential) calories for cement, glass, steel, fiber (textiles), lumber, and paper from Table E28 (p. E68); (converted to kg basis) from Odum et al., 1981.

Other values are as follows:

Food data from Burnett, 1978

Average developed for meats:

Beef (74/3834)(3.79 Cal/g) + Chicken (2373/3834)(2.39 Cal/g) +
Pork (271/3834)(3.08 Cal/g) + Fish (253/3834)(1.03 Cal/g) +
Dried Meat (2.3/3834)(5 Cal/g) = 2.76 Cal/g

Average for Grain:

Wheat, etc. (11395/12728)(3.3 Cal/g) + Rice (1333/12728)(3.0 Cal/g)
= 3.33 Cal/g.

Sugar is empirical

Fruit and Vegetables: average from Burnett, 1978.

Assorted machinery consisting primarily of steel is taken as having the same value.

Dried milk is approximately 10% moisture: (.65 E3 Cal/kg)/.1 = 6.5 E3 Cal/kg

Chemicals

Misc. mfg. goods.

(3) Embodied Solar Calories of agricultural products was determined by insolation divided by output per unit area.

Natural contribution of energy to other commodities determined by subtracting fossil fuel energy from total embodied energy - See references 4 and 5.

Values for the following from Burnett, 1978.

Meat: (481 E3 Cal/ha·yr)(1 kg/2.76 E3 Cal) = 174.3 kg/ha·yr

(5.738 E-3 ha·yr/kg)(170 Cal/cm^2·yr)(1 E8 cm^2/ha) = 9.755 E7 Cal/ha

Milk: (5000 E3 Cal/ha)(1 kg/.65 E3 Cal) = 7.69 E3 kg/ha

(1.30 E-4 ha/kg)(170 E8 Cal/ha) = 2.21 E6 Cal/kg

At 90% H_2O, dried milk is approximately 2.21 E7 Cal/kg

Wheat: average value of 11014 E3 Cal/ha.

(11014 E3 Cal/ha)(1 kg/3.33 E3 Cal) = 3.31 E3 kg/ha

(3.02 E4 ha/kg)(130 E8 Cal/ha) = 5.14 E6 Cal/kg

(4) Values generated by dividing process heat figures from the 1977 Census of Manufacturers for particular industries by the output of those industries.

Paperboard

1977 U.S. Production = 29006 E ST = 5.8 E10 lb

= 2.63 E10 kg

from 1982 Commodity Yearbook

1766.4 E3 BBL (dist. oil) = 2.595 E12 Cal (10200) = 2.647 E16

32886.4 E3 BBL (res. oil) = 5.213 E13 Cal (10200) = 5.317 E17

2926.3 E3 ST (coal) = 1.735 E13 Cal (5800) = 1.180 E17

129.5 E9 ft^3 (gas) = 3.423 E13 Cal (11356) = 3.888 E17

10694.1 E6 KWH (elect.) = 9.197 E12 Cal (27200) = 2.502 E17

1.315 E18 GSC

from 1977 Census of Manufacturers

1.315 E18 GSC/2.03 E10 kg = 5.0 E7 GSC/kg

Pulp 1977 U.S. production = 49132 E3 ST = 4.457 E10 kg

from 1982 Commodity Yearbook

= 338.3 E3 BBL (dist. oil) = 4.97 E11 Cal (10200) = 5.07 E15

17.6 E9 ft^3 (gas) = 4.65 E12 Cal (11356) = 5.28 E16

2136.2 E6 KWH (elect.) = 2.68 E12 Cal (27200) = 7.31 E16

1.310 E17

from 1977 Census of Manufacturers

1.310 E17 GSC/4.457 E10 kg = 2.94 E6

Sugar (cane sugar refined) 10453 E3 MT (U.N. Yearbook - 1977 Stats.)

209.9 E3 BBL (dist. oil) = 3.08 E11 Cal (10200) = 3.145 E15 GSC

2043.5 E3 BBL (res. oil) = 3.24 E12 Cal (10200) = 3.304 E16 GSC

17.5 E9 ft^3 (gas) = 4.63 E12 Cal (11356) = 5.253 E16 GSC

116.9 E6 KWH (elect.) = 1.005 E11 Cal (27200) = 2.735 E15 GSC

9.145 E16

from 1977 Census of Manufacturers

9.145 E16 GSC/10453 E6 kg = 8.74 E6 GSC

Cement 71200 E3 MT (U.N. Yearbook - 1977 Stats.)

727.4 E3 BBL (dist. oil) = 1.07 E12 (10200) = 1.09 E16

5892.1 E3 BBL (res. oil) = 9.34 E12 (10200) = 9.53 E16

10567.5 E3 ST (coal) = 6.27 E13 (6500) = 4.26 E17

93.1 E9 ft^3 (gas) = 2.46 E13 (11356) = 2.79 E17

9822.7 E6 KWH (elect.) = 8.45 E12 (27200) = 2.30 E17

1.40 E18 GSC

from 1977 Census of Manufacturers

1.04 E18 GSC/71200 E6 kg = 1.463 E7

Steel 113701 E3 MT (U.N. Yearbook - 1977)

7074.9 E3 BBL (dist. oil) = 1.04 E13 (10200) = 1.06 E17

36973.3 E3 BBL (res. oil) = 5.86 E13 (10200) = 5.98 E17

20887.5 E3 ST (coal) = 1.24 E14 (6500) = 8.42 E17

536.6 E9 ft^3 (gas) = 1.42 E14 (11356) = 1.61 E18

58613.2 E6 KWH (elect.) = 5.04 E13 (27200) = 1.37 E18

4.528 E18

from 1977 Census of Manufacturers

4.528 E18/113701 E6 kg = 3.982 E7

Glass Bottles - 11825 E3 MT (U.N. Stats. 1977)

2482.5 E3 BBL 9(dist. oil) = 3.65 E12 3.72 E16

1896.8 E3 BBL (res. oil) = 3.01 E12 3.07 E16

96.9 E9 ft^3 (gas) = 2.56 E13 2.95 E17

4592.5 E6 KWH (elect.) = 3.95 E12 1.07 E17

4.708 E17

from 1977 Census of Manufacturers

4.708 E17/11825 E6 kg = 3.98 E7

Plastics - 11232 E3 MT - Commodity Yearbook

1517.8 E3 BBL (dist. oil) 2.27 E16

2825.1 E3 BBL (res. oil) 4.57 E16

230.7 E3 ST (coal) 9.30 E15

31.4 E9 ft^3 (gas) 9.43 E16

14045.4 E6 KWH (elect.) 3.28 E17

5.00 E17

from 1977 Census of Manufacturers

5.00 E17/11232 E6 kg = 4.456 E7

(5) Total embodied energy (exlcluding labor) is the sum of columns 3 and 4. Data for cement, glass, steel fiber, wood, paper and plastic from p. E9, Odum et al., 1981.

(6) Calories are based on dollars paid for imports on a kg basis. Conversion of 8.437 E7 GSC/$ = see reference to Flow 14.

(7) Total Calories are equal to (Calories/kg) times the quantity imported. Labor is excluded here but is accounted for under "services". Reference Flow 14.

(8) Energy Transformation Ratio is the sum of the total embodied energy and labor divided by the heat value of the commodity.

APPENDIX D

Footnotes to Table 5: Exports from St. Lucia, including calculations of energy values.

Notes to Table 5:

(1) All weights are from the 1980 Yearbook of International Trade Statistics, U.N.

(2) Actual Calories

- a) Bananas - Pimentel
- b) Paper Products - based on typical combustion value for cellulose tissue, dry
- c) Coconut Oil - based on combustion value for lauric acid [fatty acids are typically between 8 and 9 Cal/g]
- d) Pulp - based on 10% moisture content, value is similar to that of paper-wood
- e) Oil Residues - assumed to be not fully processed constituents of oil: similar value
- f) Nuts - to be evaluated
- g) Fodder - to be evaluated
- h) Fruits - to be evaluated
- i) Soap - same value as oil, which is its major constituent
- j) Clothes - from Table E28, Odum et al., 1981
- k) Chemicals - see Import table
- l) Vegetables - Burnett, 1978
- m) Bran - to be evaluated
- n) Spices - to be evaluated

(3) Bananas

From CRC Hanbook of Energy Utilization in Agriculture p. 294 Central Taiwan

Output $\sim$ 19,000 kg/ha = 1.9 kg/m^2

So (48986 E3 kg/(1.9 kg/m^2) = 2.58 E7 m^2

[leaves 2.29 E7 m^2 for other tree crops; nuts, cocoa, spices and coconuts]

Nat. GSC cals for bananas (based on Chem. Pot. Rain) =

(2.58 E7 m^2)(2.56 E3 Cal/m^2)(6.9 E3 GSC/Cal) =

(4.56 E14 GSC)/48986 E3 kg =

9.30 E6 GSC/kg

Vegetables

Natural:	Potatoes	34384 kg/ha	
	Spinach	11200	
	Tomatoes	49616	
	B. Sprouts	12320	
	Casava	5824	(Africa)
	Beans	1457	
	Cowpeas	1530	(Nigeria)
	Peanuts	1280	(Thailand)

117,611 ÷ 8 = 14701 kg/ha

Chem. Potential of Rain

(2.56 E3 Cal/m^2)(6.9 E3 GSC/Cal)(1 E4 m^2/ha)/(14701 kg/ha) = 1.2 E7

Coconut Oil, Soap, Residues

Dominica: 1182 E3 kg Oil

2801 E3 kg Soap

3983 E3 kg Coconut products

6725 acres (2.72 E7 m^2) in coconuts

So (2.72 E7 m^2)/(3983 E3 kg) = 6.83 m^2/kg

(6.83 m^2/kg)(2.56 E3 Cal/m^2)(6.9 E3 GSC/Cal) = 1.207 E8 GSC/kg

Nuts, Fruits, Spices

Bananas use 2.58 E7 m^2

Coconut products use (6.83 m^2/kg)(2786 E3 kg) = 1.904 E7 m^2

Total tree crop area is 4.87 E7 m^2

Bananas, coconut	4.48 E7 m^2
Spices, etc.	3.86 E6

(3.86 E6 m^2)/(2.037 E6 kg) = 1.90 m^2/kg

(1.90 m^2)(2.56 E3 Cal/m^2)(6.9 E3 GSC/Cal) = 3.35 E7

Paper Products, Pulp

Given a total embodied energy of 27.2 E6 GSC/lb (6 E7 GSC/kg) and a fossil fuel contribution of 5 E7 GSC/kg (Section (4)) this leaves a natural contribution of 10 E6 GSC/kg.

Fodder

From Pimentel, avg. yield for hay, alfalfa and silage is (4.2852 E4)/3 = 1.43 E4 kg/ha.

Using Chem. Pot. Rain:

(2.56 E3 Cal/m^2)(6.9 E3 GSC/Cal)(1 E4 m^2/ha)/(1.43 E4 kg/ha) = 1.237 E7

(4) Fossil fuel requirements for coconut oil processing (and oil residues) unknown at this time.

Values for nuts, speices, bran and fruits are also unknown but these commodities do not require substantial processing.

Bananas:

Fossil fuel requirements:

Gas = 30 l (8179 Cal)(11492 GSC) = 2.82 E9

Diesel = 100 l (9235Cal)(11492 GSC) = 1.06 E10

Elect. = 48 KWH (860 Cal)(27200 GSC) = 1.12 E9

N = 352 kg (.487/g)(1.9 E5) = 3.26 E10

P = 176 kg (.382/g)(1.99 E6) 1.34 E11

1.81 E11

1.81 E11/19000 kg = 9.52 E6 Cal/kg

Note - if productivity is lower than Taiwan the Natural cost /kg will increase while the net GSC/kg will then decrease for fruits, nuts, spices.

Vegetables:

Fossil fuel requirements:

Sums of fuel, N, P, for the above items divided by total yield.

1056 l diesel	(9235)(10200)	9.95 E12
900 l gas	(8179)(10200)	7.51 E10
57 KWH	(860)(27200)	1.33 E9
1041 kg N	(.487)(1.9 E5)	9.63 E10
823 kg P	(.382)(1.99 E6)	6.26 E11
		8.98 E11

(8.98 E11 GSC/ha)(117611 kg/ha) = 7.63 E6

Fodder - Pimentel - sum of hay, alfalfa, corn silage

Fuel =	275 l diesel		9235 (10200)	2.59 E10
	105 l gas		8179	8.76 E9
N =	130 kg	.487	1.9 E5	1.20 E10
P =	119 kg	.382	1.99 E6	9.05 E10
				1.37 E11

1.37 E11 GSC/4.2852 E4 = 3.20 E5

(5) Sum of Columns 3 and 4

(6) Value of labor is generated by dollars received for export times the domestic calorie/$ ratio divided by the weight of the commodity to give a per kg basis.

Dollar values and weights from Yearbook of International Trade Statistics, U.N., 1981

Calorie/$ ratio from Reference fo Flow 17.

(7) Column 5 (Total Calories/kg) times the quantity exported

(8) Energy Transformation Ratio: sum of all embodied energies divided by heat value of a commodity. See text for explanation.

APPENDIX E

Calculations of calorie to dollar ratios and energy analysis ratios to accompany Table 3.

Energy to Dollar Ratio

Domestic Cal/$ = [Natural + Fuel + Fertilizer + Imported Goods
+ Imported Services - Exported Goods]/[GDP + Exported Services]

(1.09 E16 + 2.15 E15 + 1.85 E14 + 1.07 E15 + 6.6 E15
Rain Fuel N P Goods
+ 9.01 E15 - 1.88 E15) = 2.804 E16
Services Exports

(99.04 E6 + 65.59 E6 + 33.4 E6) = 198.03 E8
GDP Exports Tourism

2.804 E16 GSC/$1.98 E10 = 1.416 E8 GSC/$
= 2.08 E4 CE/$

Energy Analysis Ratios:

Based on Rain Chem. Potential. All data from Table 1.

Net Energy = [Fuel + Fertilizer + Goods + Services (I)
- Exports - Services (E)]
= 5.94 E 15 GSC
i.e., 5.94 E 15 GSC are added to the economy each year

Yield Ratio = [Exports + Services (E)]/[Fuel + Fertilizer + Goods + Services (I)]
= 1.308 E16/1.902 E16
= .687

Investment Ratio = [Fuel + Fertilizer + Goods + Services]/[Natural]
= 1.902 E16/1.09 E16
= 1.745

Energy Added Factor = [Exports + Services (E)]/Natural
= 1.308 E16/1.09 E16
= 1.20

APPENDIX F

Description of Energy Language Symbols with example to accompany Figure 1.

The basic elements of energy language are depicted in Figure 1 and are described below.

a) Storage: represents a quantity that is not necessarily a function of time that is within the system of interest. Any quantity in storage represents potential energy and is therefore a force. Examples might be dollars in the economy or the biomass of a cloud forest.

b) Flow: represents the movement of matter or energy over a period of time and are driven by forces (storages and potentials) or external sources. Examples are the flow of water and human labor acting on a farm.

c) Sources are energies arriving from outside the system boundary which are responsible for driving most of the processes in nature and the economy. Sunlight and fossil fuels would be external sources since they are not created within the system.

d) Heat sinks belong on all storages, interactions and on many flows. They represent thermodynamic losses in terms of depreciation, entropy and mechanical inefficiency. Land erosion and power line losses are examples of necessary heat sinks on the island.

e) Interactions (work gates) show how energies of differing quality combine to yield new energy in another form. Sun, carbon dioxide and water interact to produce biomass; labor, fuel and pumps interact with groundwater to produce irrigation water which has a higher potential for use.

f) Constant gains represent fixed amplifications along a pathway. In this model population growth is assumed to have a constant rate of increase which is made possible by the overall flow of energy in the economy.

g) Producers are generalized photosynthetic units that upgrade low quality (solar) energy into materials for use by other organisms, ie., farms and forests.

h) Consumers are self regulating units that are dependant on upgraded energies (food, fuel and industrial materials) to survive.

i) Money exchanges or price mechanisms show that money flows opposite to energy in certain proportions which can be regulated by a pricing function that either changes in time or is dependant on changes in either the world or the domestic economy. These changes could be shown by a source pumping energy in the form of information into the price mechanism.

j) Processes are complex arrangements of storages and flows in which the details of structure are not of significant interest, Of concern are the inputs and outputs only, Summary diagrams of subsystems and even the entire economy are typically viewed in this manner.

k) Sensors are mechanisms by which information can be gotten about rates of flows or the size of storages in the system without significantly affecting the quantities of interest. Information from sensors is typically used to control flows. For example, information about the island's "image" controls the rate at which tourists will visit.

APPENDIX G

Calculations to accompany Figures 5-7.

Calculations to accompany Figure 5 (Geothermal Potential)

Energy delivered to consumers: (16.5 E12 Cal)(27200 GSC/Cal = 4.48 E17

Operations: (700 E9 PE)(7.77 E3 GSC/PE) = 5.44 E15

Investment: (4443 E9 PE)(7.77 E3 GSC/PE) = 3.45 E16

Embodied energy of steam input taken as equivalent to plant output

= 5.09 E17

* Conversion of 7.77 E3 GSC/Cal PE based on Gilliland's ratio of 16,500

Cal elect. = 57,750 PE

Using 27,200 GSC/Cal electric yields 7771 GSC/PE

Net Yield Ratio = 4.48 E17/3.45 E16 = 13

Investment Ratio = 3.45 E16/5.29 E17 = 0.07

Calculations to accompany Figure 6 (Tourism)

Fuel: (5.5%)(2.15 E15 GSC) = 1.18 E14 GSC

Electricity: (22.3%)(1.32 E15) = 2.94 E14 GSC

Sum = 4.13 E14 GSC

Labor ($) = (2890)($480) = $1.39 E6

Labor = ($1.39 E6)(1.24 E8 GSC/$) = 1.73 E14 GSC

Services ($) as follows:

33.4 = Serv. + Labor + .293 (Serv. + Labor)

= X + 1.39 + .293 (X + 1.39)

X = 24.44 E6

Returns ($) = (.293)(24.44 + 1.39) = 7.57 E6

Taxes ($) = (.45)(7.57) = 3.40 E6

Goods (11.4%)(6.6 E15) = 7.52 E14

Services (11.4%)(7.96 E15) = 9.07 E14

Sum = 1.66 E15

Investor Services (Loans) = ($7.57 E6)(8.437 E7 GSC/$) = 6.39 E14

Government Services (Taxes) = ($3.42 E6)(1.24 E8 GSC/$) = 4.22 E14

Natural energy = total of population and visitors = 4.62 E7 "man-days". Total of visitors (based on average length of stay = 8.6 days) is 6.43 E5. Percentage of natural energy consumption is 1.4% (0.014)(10.9 E15) = 1.52 E14

Value of Tourist Dollars = ($33.4 E6)(8.437 E7 GSC/$) = 2.82 E15

Sum of High Quality Inputs = 3.30 E15

Sum of All Inputs (Embodied Energy of Tourist Service) = 3.45 E15

Investment Ratio = 3.30 E15/1.52 E14 = 21.7

Yield Ratio = 2.82 E15/3.45 E15 = 0.82

= 3.45 E15/2.82 E15 = 1.20

Calculations to accompany Figure 7 (Banana Industry)

Natural energy: (9%)(10.9 E15) = 9.81 E14

Goods: Hard goods were $41.9 E6 out of $82.8 E6 in 1978 (50.6%)

Agriculture and Fisheries were $28.5 out of $135.6 (21%)

Agricultural activities taken as 90% of this yields (19%)

(.19)(.50) = 9.5%

(.095)(6.6 E15) = 6.27 E14

Services: (.095)(7.96 E15) = 7.56 E14

Sum = 1.38 E15

Services ($) = (.095)(82.8 E6) = 7.87 E6

Labor ($): (Sales value) - (Services)

12.11 E6 - 7.87 E6 = 4.24 E6

Labor: ($4.24 E6)(1.70 E8 GSC/$) = 7.22 E14

Sum of High Quality Inputs = 3.36 E15

Investment ratio = 3.36 E15/.98 E15 = 3.4

Net energy yield ratio = 2.98/3.36 = .89

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