Enoch, H.Z. 1977. A theory for optimalization of primary production in protected cultivation: I. Influence of aerial environment upon primary plant production. Contr. No. 276-E, 1977 series, The Volcani Center, Bet-Dagan, Israel. 31-43.

An analysis of plant production in greenhouses is presented which emphasizes the energy costs and compares protected cultivation with other agricultural systems. An estimate is

Table 1: Production of winter lettuce in heated greenhouses in England.

	Input (Running costs only)	Million BTU per acre
1.	Fuel oil heating (82 to 109 tons, British).	1543 - 2063
2.	Propane for CO_2 enrichment (5.34 British tones).	119
3.	Electricity for lighting seedlings (3890-14260 kWh).	22 - 79
4.	Fungicides (224 lbs. 100% solution × 95 MJ/kg).	4
5.	Fertilizers (1.5 lbs. superphosphate × 17 MJ/kg).	0 - 5
6.	Seedling sprays (29 lbs. at 95 MJ/kg).	0.5
7.	Sundries (not specific) 74 × 153 MJ/lbs. sterling).	4
8.	Boxes (15400 or 3.5 British tons at 30.6 GJ/ton).	41
9.	Seed and blocking compost (300 × 150 MJ/lb. sterling).	17
10.	Labor (2870 hrs. × 0.7 MJ/hr.).	1
	TOTAL:	1752 - 2333

Output

15,400 boxes of lettuce × 12/box = 184,800 heads of lettuce estimated at 1.5 kg lettuce per box = 23.1 British tons of lettuce at 0.46 MJ/kg lettuce.	4.1

Ratio

Energy input per head of lettuce	10-12 Thousand BTU
Energy input per 2.2 lbs. lettuce	77-100 Thousand BTU

Energy out-in ratio ER = 0.0017-0.023 about 0.002.

NOTE: Values in original table have been converted to British thermal units (BTU) per acre from gigajoules per hectare. The ER ratio should remain about the same.

given for the energy expenditure needed to provide light, CO_2 and heat in the greenhouse. A model of net photosynthesis rate as a function of light, CO_2 and leaf temperature is used to compare the CO_2 uptake rate of a spray carnation (C_3 plant) inside and outside the greenhouse at selected environmental conditions.

The greater part of the greenhouse industry produces plant products at a location and time where such products cannot be obtained outside. In this analysis, the energy requirements of different agricultural systems are examined with emphasis on protected crops. The effects of light, CO_2 and temperature on primary production are calculated.

Conventional methods for calculating energy uses are to determine the total non-solar input needed to produce a particular product. This energy input can be calculated up to the point when the product leaves the farm, or is served on the consumer's plate. The energy content of the product may be its total caloric value, the harvested part, or the digestible part. An energy analysis may look like the one presented in Table 1 for winter lettuce production in greenhouses in England (Leach, G., 1975, Energy and food production. Publ. Int. Inst. for Environment and Development), giving an "energy output to input ratio" (ER) of 0.002. Selected examples for other branches of agriculture are given in Table 2. It can be noted that primitive agricultural systems have the highest ER's, and the lowest output per unit area and time. Protected cultivation and fisheries are about 10 times less efficient than animal production, and 100 times less efficient than grain production and mixed agriculture. The ER for a perennial rose crop in Israel was calculated to be 0.031, with an energy input of 4454 MBTU per acre per year (1 MBTU = 1,000,000 BTU). As solar radiation in Israel is 2982 MBTU $Ac^{-1} yr^{-1}$, the non-solar energy input amounts to nearly 15% of the solar energy input. Even if production rates equivalent to poten-

Table 2: Energy budgets for various types of agriculture.

Type of agriculture	MBTU per acre per year output	ER energy ratio
I. Shifting cultivation, Congo	6	65
Nomad, Bedouin, Sinai	0.08	50
Tsembaga Yam Gardens, N. Guinea	0.54	16.5
Subsistence farming, India	4	14.8
Kung Bushmen, Africa	1.1	7.8
Dodo tribe, Uganda	0.32	5
II. Rice, Phillipines	8.8	5.5
West Bank, Israel, 1968/70	1.3	4.1
Cereal, England, average farm 1970	18.7	1.9
Allotment garden, England, 1974	23.1	1.3
Intensive rice, USA	32	1.3
Carrots, England, 1970/71	11.6	1.1
III. Cattle and sheep, England	3.6	0.59
Dairy, England, 1970/71	7	0.55
Israel, pre-1967 borders	12.6	0.41
Pig and poultry, England	15	0.32
Brussel sprouts	3.5	0.19
IV. Fisheries, England, 1969	1.3 million MBTU	0.050
Heated greenhouse, roses, Israel	137	0.031
Heated greenhouse (2 months) Winter lettuce, England	24.5	0.002

tial gross production of 870 MBTU $Ac^{-1}\ yr^{-1}$ could be achieved, the ER would still be only 0.20. It thus appears that greenhouses must remain a high energy consuming branch of the agricultural production system, and that improvements in primary production are unlikely to raise the ER to one.

The energy utilized in producing photosynthetically active radiation from lamps can be estimated: Incandescent lamps yield 6 to 12%, and fluorescent, mercury and metal halide lamps yield 20 to 24%, of the supplied electrical energy in the form of visible light. Of the total, 70% is directed down toward the plants by reflectors, with the efficiency of the electrical supply by the power company estimated at about 25%. Incandescent lamps thus have an overall efficiency of (0.06 × 0.70 × 0.25) or 0.0105 (1%) and for the higher range 2%. More efficient lamps range from 3.5 to 4.2%. Thus we need 25 to 100 watts per sq. meter (2.3 to 9.3 watts per sq. ft.) fossil fuel energy to obtain 1 $W\ m^{-2}$ photosynthetically active energy on the plants. In other units, the energy input is between 1501 and 6083 MBTU per acre per year per watt per square meter photosynthetically active energy from lamps.

By increasing CO_2 concentration in greenhouses, the output can be increased. For glasshouses under British conditions, an average of 370 pounds CO_2 per acre was used to raise the CO_2 concentration 1 ppm. As 1 lb. of propane yields 1.36 lbs. of CO_2, an additional concentration of 1 ppm CO_2 would require 141 lbs. of propane per acre per year. The energy requirement associated with this amount is 5.7 MBTU per acre per year. Heating in England's climate uses about 1101 MBTU with CO_2 enrichment to 1000 ppm raising the temperature approximately 4.3°F.

The author developments a model of photosynthesis for spray carnations in greenhouses, using factors of available light, CO_2 concentration and leaf temperature. The idea is that the energy costs of an additional produced unit can be calculated. The result agrees with conventional wisdom in that increasing CO_2 concentration becomes more effective the higher the light input. Inside was compared with outside, showing that without CO_2 enrichment, the indoor photosynthetic rate is less than the outside, with the break even point at about 600 ppm. If the light transmission of the greenhouse decreases from 80 to 60% of the outside, CO_2 concentration must be raised to 1600 ppm in order to equal the outdoor rate. Leaf temperature between 50 and 86°F had only a slight effect on photosynthesis at 300 ppm CO_2, with the loss in primary production by growing the crop in a greenhouse becoming larger with increasing temperatures and increasing light energy. Under certain conditions, the net photosynthesis rate inside a greenhouse can be lower than outside.

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