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THE SOLAR ENERGY CONVERSION THROUGH SEAWEED PHOTOSYNTHESIS AND ZERO EMISSIONS POWER GENERATION

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Introduction

Seaweed is not new thing in the world industry, still limited mostly in food and pharmacy. Let us look at the report of Irish Galway institute , quoting some specific difficulties:

These difficulties and the size of the Irish industry should be considered in relation to the international seaweed industry. About 7 million t of seaweeds (wet weight) were produced world-wide in 1993 of which some 65% was food-grade (Anon. 1997). Brown algae accounted for 4.9 million t of which Chinese production alone of the food kelp Laminaria japonica was 4 million t alone. Japan produced an additional 300,000 t of this kelp making a total in 1995 of about 4.3 million t, which probably makes Laminaria japonica the largest single-species crop produced by aquaculture in the world. Some 250-300,000 t of this material is used in China to make about 7,000 t of alginates, viscous polysaccharides used in a wide variety of industrial applications, particularly in the food industry. In addition, Japan and Korea in 1993-4 produced about 21,000 million sheets of nori (about 550,000 wet t). Nori is a red alga (mainly Porphyra yezoensis), and this crop is worth about US$1.5 billion, the most valuable single-species crop produced by aquaculture in the world. The third most valuable food species is wakame (Undaria pinnatifida) of which 750,000 t were produced in Japan, Korea and China in 1995. In 1995, by contrast, the only European production of seaweed by aquaculture was 8 wet t of wakame in Brittany, and even this small amount was more than adequate to satisfy demand.

Most of the remaining seaweed harvesting and aquaculture goes to fuel the production of the three families of seaweed polysaccharides known as seaweed gums: alginates from brown algae, and carrageenans and agars from red algae. The wholesale value of these gums is about US$560 million. The total worth of the international seaweed business exceeds US$4.5 billion of which Ireland has only a very small percentage.

Algae cultivation for electricity generation is discussed in some recent decades . All algae have been divided by microalgae (size of some microns) and macroalgae or seaweeds, which are much greater. The photosynthesis is similar in the both kinds and the early history we will start from microalgae. But the technical problems of cultivation and combustion are different, that is why we will focus on macroalgae only.

First published results of the use of open ponds with microalgae to convert carbon dioxide from power plants into methane fuel belong to Golueke and Oswald (cited in [1]). They demonstrated a small system, involving microalgae growth, digestion to methane and recycle of nutrients. They tried to catch CO_2 injecting the flue gases into the pond regardless to a very small fraction of CO_2 in flue gases, about 10%. Then especially active was Solar Energy Research Institute SERI (now NERL) in "Aquatic species program". After the testing of the three outdoor algae facilities in California, Hawaii and New Mexico it was concluded that it is possible to produce microalgae in a large-scale pond at high productivity and relatively low cost.

Similar results published Alexejev et al.[2] from Moscow University, demonstrating a small microalgae system "Biosolar" with production of 40 g/m^2 dry biomass in a day. The mineralized elements from the tank of produced methane are reused by algae. CO_2 is restored after burning. They stated " 1 mtce of methane might be produced from a surface of 70 m^2 annually."

Chemistry of algae pond was described by L.Brown [3, 4] along with the outlook of a raceway-type pond and a paddle-wheel to move water. The overall reaction for photosynthesis by cianobacteria, micro- and macroalgae is as follows:

$$CO_2 + H_2O + \text{light} \Rightarrow CH_2O + O_2 \quad (1)$$

He also stated: "We estimate that microalgal biomass production can increase the productivity of desert land 160-fold (6 times that of a tropical rainforest). Microalgae require only 140-200 lb of water per pound of carbon fixed even in open ponds and this water can be low-quality, highly saline water".

If the pond water is rich with nutrients like a wasted municipal water or released from an animal farm the very high figures of dry biomass production have been published: 120 g/m^2 in a day [5] or 175 g/m^2 day by Pulz (cited in[6]). These figures translate into 40–50 kg/m^2 annually.

In parallel to the ponds developments some schemes of relevant power plants to use produced biomass as a fuel have been proposed. Patent by Yamada [7] contains the use of dry algae as an addition to the regular fuel. A fraction of flue gases is released to atmosphere by a stack, the rest is directed to an absorption tower to be washed by water, which dissolves CO_2 from the flue gases and returns it to the pond. The sore point of this scheme is rather small fraction of CO_2 in flue gases, where the dominant gas is the inert nitrogen. The separation of CO_2 from nitrogen turned out to be an insurmountable problem.

The radical solution, the separation of nitrogen not after, but before combustion has been described by Yantovski [8]as the cycle entitled SOFT (Solar Oxygen Fuel Turbine). Further development of the SOFT cycle see below.

Combustion of biomass in the "artificial air", the mixture of oxygen and steam or carbon dioxide, gives the flue gases without nitrogen . The CO_2 might be returned in the pond to feed algae .

Data on Ulva growth

Crucial data for the SOFT project are productivity of Ulva under natural insolation and by ordinary sea water temperature and chemical composition. There exists an experience of Ulva harvesting in Irish island [20], where it is quite abundant. Aside to Ulva exists a number of similar highly productive seaweeds.

Let us try to evaluate a possible growth rate of macroalgae with dimensions of a branch from one to ten of millimetres. For simplicity assume the form of organic matter particle as a sphere.

Its volume $V = 4/3\pi r^3$ and crosssection surface $A = \pi r^2$. Solar energy flow density (insolation) δ =220 W/m^2. Low heating value of produced organic matter H= 19000 J/g, the biomass density ρ= 800 kg/m^3, efficiency of photosynthesis η = 0.1.

As the result of photosynthesis the sphere radius is increased

According to standard definition of the relative growth rate RGR = M'/M, where M'= rate of mass increase in a second or in a day and M= mass of organic particle, we have:

$$M'/M = RGR = (3/4)\delta\eta/H\rho r, \qquad \text{In time increase } M(t) = M_o \exp(t \cdot RGR) \quad (2)$$

Actual problem is the change of RGR in time, when (2) is invalid.

In this formula least known are the two quantities, the efficiency of photosynthesis (assume it as 0.1) and the size of a considered particle (assume r=1mm). With these rather preliminary assumptions we have M'/M=RGR= (3/4) 220x 0.1/(19000x800 000x0.001 = 0.108 10^{-5} 1/sec = 0.09378 ~ 0.1 1/day.

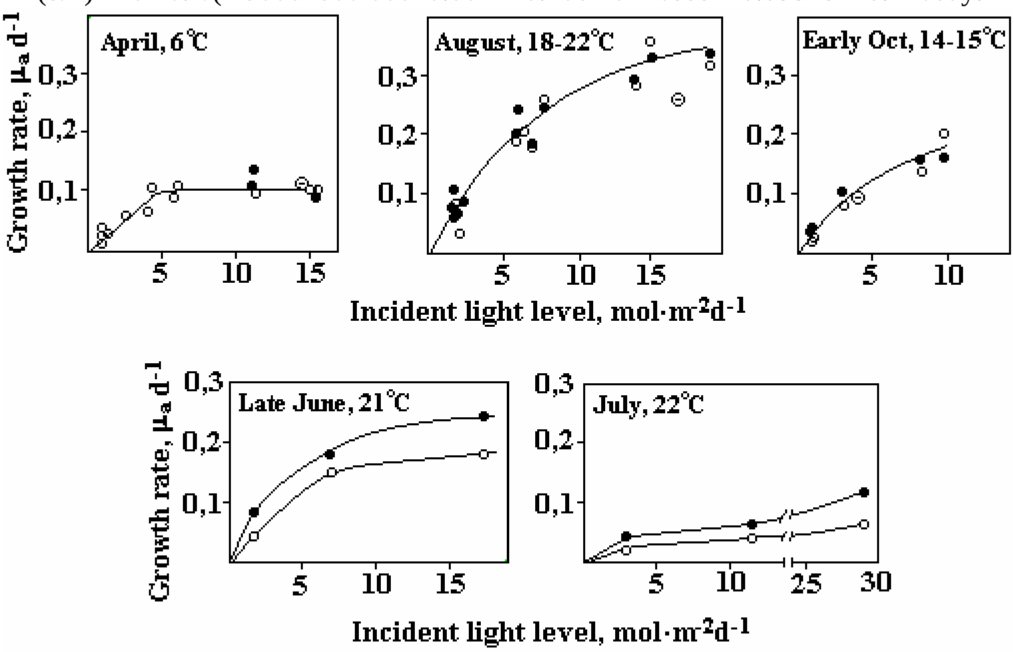


Fig.1,a. Growth of Ulva lactuca versus insolation. Black dots reflect - with addition of inorganic nitrogen, open dots-without [22]

The result is in agreement with observed data. It is evident: the more is r the less is RGR. In some research is indicated the decline of RGR after a size of particles is achieved.

The direct measurement of the Ulva lactuca growth by different insolation in shallow water (40 to 70 cm) in the Roskilde Fjord, Denmark has been made by O. Geertz-Hansen and K. Sand-Jensen in 1992 [22]. They measured surface area A of initially17 mm diameter Ulva disks. Growth rates denoted μ_o were calculated as RGR = μo = ln(A/Ao)/t, where t = days of incubation.

Experiments vividly show the conversion of solar energy into chemical energy of Ulva biomass at the rather high latitude of Denmark, see Fig.1a. At all 5 graphs are presented RGR in unit 1/day versus local insolation in mol/sq.m.day. The last unit should be converted in our convenient units W/sq.m. Here mol= mol of foton = 1 einstein = 210 kJ and day = 86400 sec, hence 10 mol/m^2.day = 24.3 W/m^2. Most important data are rather high growth rate (up to 0.3 1/day) in natural conditions of 55 grad of latitude by modest insolation and real temperatures. In Israel it might be much higher due to warm winter.

Most productive seaweed Ulva is working already for water cleaning (denitrification). The experience is of value for SOFT cycle.

Table 1. Ulva production in denitrification ponds [18]

A)

File name: Ulva.xls		
Phytotreatment pond average condition		
Ulva biomass (Kg fw m^3)		1,5
Water depth (m)		1,0
Temperature range (C°)		15-30
Light intensity range (uE m^{-2} s^{-1})		500-2000
pH range		7-8
Experimental measurements		
Ulva Growth rate (d^{-1})		0,1
Ulva assimilation rates (umol N d^{-1} m^{-2})		40000,0
User-Friendly Tool		
INPUT		INPUT
Pond Area (m^2)	enter value >	1300,0
Water Flow (l s^{-1})	enter value >	250,0
Ammonia in inlet water (uM)	enter value >	179,0
Nitrate in pond water (uM)	enter value >	6,0
OUTPUT		
Biomass to be removed daily (Kg fw d^{-1})		195,0
Denitrified nitrogen(%)		0,04
Assimilated nitrogen(%)		1,3
Total nitrogen removal (%)		1,4
Ammonia in outlet water (uM)		176,5

B)

File name: Ulva.xls		
Phytotreatment pond average condition		
Ulva biomass (Kg fw m^3)		1,5
Water depth (m)		1,0
Temperature range (C°)		15-30
Light intensity range (uE m^{-2} s^{-1})		500-2000
pH range		7-8
Experimental measurements		
Ulva Growth rate (d^{-1})		0,1
Ulva assimilation rates (umol N d^{-1} m^{-2})		40000,0
User-Friendly Tool		
INPUT		INPUT
Pond Area (m^2)	enter value >	8000,0
Water Flow (l s^{-1})	enter value >	140,0
Ammonia in inlet water (uM)	enter value >	61,0
Nitrate in pond water (uM)	enter value >	6,0
OUTPUT		
Biomass to be removed daily (Kg fw d^{-1})		1200,0
Denitrified nitrogen(%)		1,21
Assimilated nitrogen(%)		43,4
Total nitrogen removal (%)		44,6
Ammonia in outlet water (uM)		33,8

As the depth of ponds here is 1 m, the dry weight of Ulva biomass is 1.5 kg per m^3 of water and growth rate 0.1/day. Daily produced biomass is 1200 kg (case B) =13.8 g/s. If assume the LHV of biomass = 19000J/g the energy flow in biomass as a fuel is 262.2 kW. Assuming a realistic efficiency of fuel into power conversion as 25% (even in small units like a microturbines or piston engines of ZEMPES) the produced power from such pond of 0.8 ha surface is 65.5 kW or 100 kW from 1.22 ha. In the subsequent calculations the same power needs 4 ha due to much less assumed Biomass productivity. It is possible, the photosynthesis in denitrification is more productive than in sea water without nitrides.

A role of nitrides mentioned in earlier work :

We recorded specific growth rates (NGR) ranging from 0.025 to 0.081 d^{-1} *for a period up to two months in the repeated short-term experiments performed at relatively low initial algal densities (300–500 g AFDW* m^{-3}*). These NGR resulted significantly related to dissolved inorganic nitrogen (DIN) in the water column. Tissue concentrations of total nitrogen (TN) were almost constant, while extractable nitrate decreased in a similar manner to DIN in the water column. Total phosphorus showed considerable variation, probably linked to pulsed freshwater inflow.*

In the long-term incubation experiment, NGR of Ulva was inversely related to density. Internal concentrations of both total P and TN reached maximum values after one month; thereafter P concentration remained almost constant, while TN decreased below 2% w/w (by dry weight). The TN decrease was also accompanied by an abrupt decrease in nitrate tissue concentration. The biomass incubated over the two *month period suffered a progressive N limitation as shown by a decreasing NY ratio (49.4 to 14.6). The reciprocal control of Ulva against biogeochemical environment and viceversa is a key factor in explaining both resource competition and successional stages in primary producer communities dominated by Ulva. However, when the biomass exceeds a critical threshold level, approximately 1 kg AFDW m^{-3}, the macroalgal community switches from active production to rapid decomposition, probably as a result of selfshading, biomass density and development of anaerobic conditions within the macroalgal beds.*

Table 2. Growth rates of algae and rates of decay [19]

Parameter	Meaning	Units	Literature value	Calibrated value
μ_{max04}	Ammonification rate	day $^{-1}$	0.045	0.1263±0.0251
μ_{max42}	Nitrification rate	day $^{-1}$	0.011	0.0010±0.000785
μ_{max23}	Nitrification rate	day $^{-1}$	0.046	0.1323±0.0147
μ_{denit}	Denitrification rate	day $^{-1}$	0.37	0.8329±0.0948
μ_{max}	Macroalgae maximum growth rate	day $^{-1}$	0.23	0.4509±0.0312
Ω_m	Macroalgae decay rate	day $^{-1}$	0.03	0.0594±0.062
SR	Ruppia decay rate	day $^{-1}$	0.041	0.0675±0.0043
ρ_{max}	Ruppia maximum growth rate	day $^{-1}$	0.17	0.3780±0.0235

Systematic measurements of Ulva growth in natural conditions of a coastal lagoon Sacca di Goro, Adriatic Sea, Italy; has been made by Viaroli et al. [23]. On the area 26 km^2 by average depth about 1.5 m by observed different chemical content of water they recorded RGR of Ulva about 0.05 -0.15 1/day. This is a renewable source of fuel for the SOFT cycle of about gigawatt range.

Macroalgae as a renewable fuel

Having looked at the growth rate of about RGR= 0.08 – 0.23 in literature and fantastic "calibrate value " RGR = 0.4509 we need to learn the main property of any fuel – the heating value. Sometimes it is called "calorific value" when measured in calories. In literature one may see rather different values from 10 to 19 MJ/kg. The thing is what means this kg, dry or wet, with ash or without. The most comprehensive seems to be the work by M.D Lamare and S.R.King [21]. Here dry algae samples are disintegrated and combusted in a bomb.

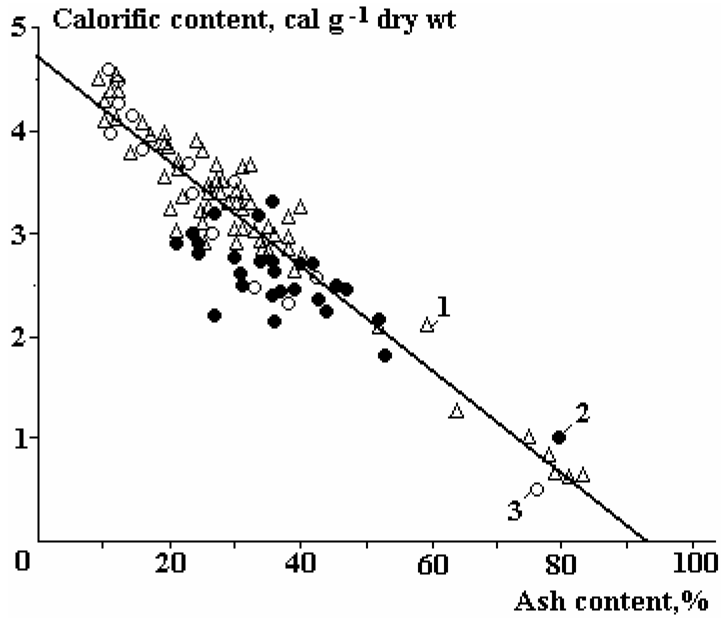


Fig.1,b. Correlation line for many algae: heating value versus ash content [21]

Extrapolating to 0 ash we see 4.7 kcal/g dry wt = 19.64 kJ/g which might be accepted for all organic matter of different algae. By 10% of ash it is about 19 kJ/g which is selected for forthcoming energy conversion calculations. As inorganic substance is absorbed from water solutions without photosynthesis it seems to be out of energy balance.

Heating value of algae depends of a season of growth, see Fig.1,b.

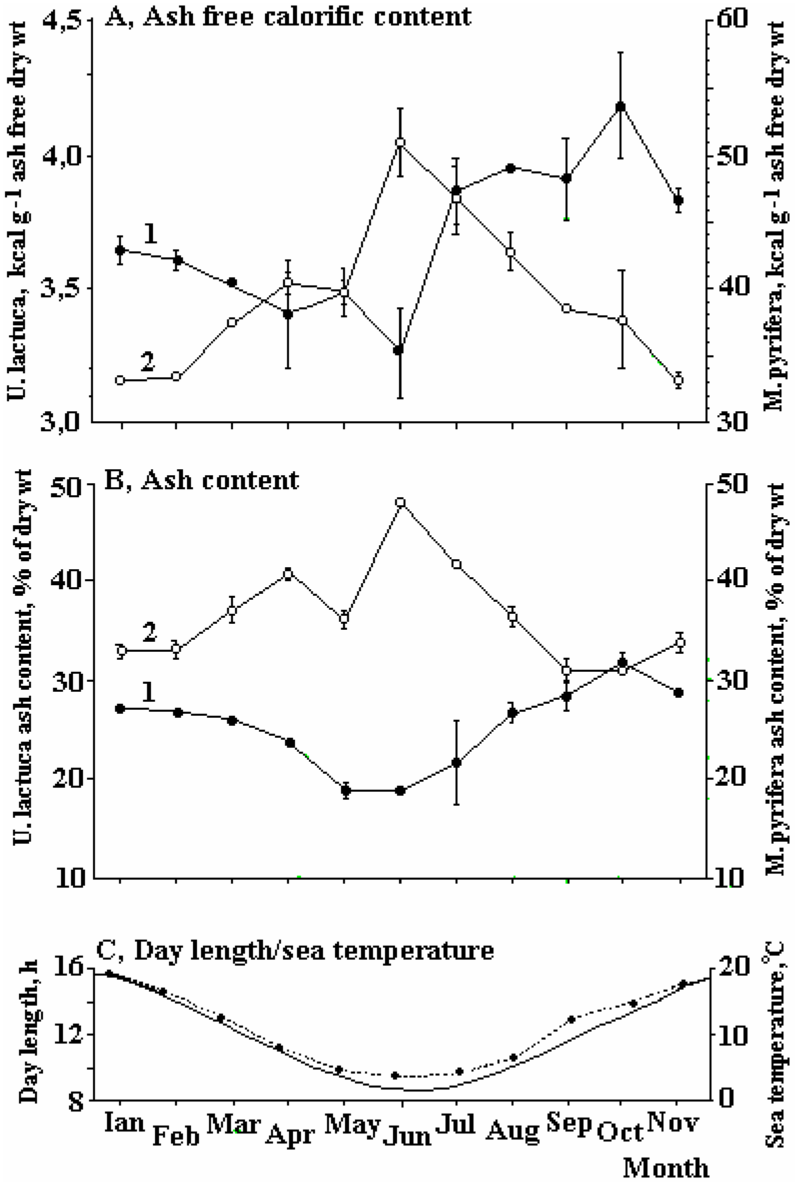


Fig. 1,c. Heating value variation in a year. In New Zeland winter is in May-Aug

In this measurements the heating value of Ulva seems to be a little less than 19MJ/kg, However we will use just this figure as more statistically proven.

Macroalgae cultivation in Israel and Italy

The crucial data for this paper are based on Israelian experience [9]. There were in 1998 three race-way-type ponds, each surface of 1500 m^2 with the paddle-wheel sea water circulation. CO_2 is supplied by a tank on a lorry and injected into water by perforated tubes. The depth of water 0.4 m, hydrogen factor pH=7. The firm figures were obtained for a seaweed *Gracilaria* only. The stable productivity of dry mass from a pond was 12 t/year or 8 kg/sq.m.year. By the use of seaweed *Ulva* the expected productivity is doubled. These ponds are located in Northern Israel, near to shore of the sea, from where the sea water is pumped into ponds. Still the produced biomass is used as raw material for chemicals and pharmaceutics. Recently some headway in seaweed cultivation had made Noritech-Seaweed Biotechnologies Ltd.

In Italy the main practical interest in Ulva seems to be concentrated in water cleaning and denitrification [16–19] where much research have been done in Genova, Venice and Parma Universities. Their active work gives an opportunity to use the SOFT cycle also as an incinerator, deflecting extra nitrides, heavy metals and other contaminants in fuel separation device to dispose it of; perhaps underground in some depth.

Energy flow concentration

The main obstacle of solar energy capture is its very low current density, especially annually averaged. In Israel it is about 220 W/m^2, only 16% of the Solar constant 1368 W/m^2. In central Europe it is a half. Thus the energy expenditure and cost of incidental energy absorber is of primary importance. In case of photovoltaics with rather high efficiency (in laboratory about 30%, in practice a half) the pure silicon absorber takes by manufacturing lots of energy and money. That is why solar cells up to now are rather expensive. As it will be shown later, efficiency of the solar energy conversion into electricity through algae pond is much less, about 3–5%. But the energy expenditure of absorber – pond is hundred times less than that of silicon.

Having been absorbed by algae the solar energy in chemical form is concentrated by water flow much better than by optical concentrator. The concentration factor of a paraboloid concave mirror is about 500, it means the averaged focal spot energy current density is about 500x220= 110 kW/sq.m.

Energy flow in the pipe from algae pond to processing is about

$$\alpha \times \rho \times V \times H = 0.001 \times 1000 \times 1 \times 19.10^6 = 19\,000 \text{ kW/m}^2 \quad (3)$$

Here α = 0.001 = mass fraction of biomass in water, ρ= 1000 kg/m^3= water density, V = 1m/s = water velocity, H = 19 MJ/kg = dry biomass heating value.

It is evident that energy current density in the pipe is hundred times more than that in the focal point of optical concentrator (Hydrodynamic concentration). It means the equipment size for the subsequent energy conversion processes should be rather small. It is more important than large size of solar energy absorber.

Power unit outlook

Schematic is presented on Fig. 2. Water with algae 6 from the pond 4 is going to the water separation unit 12, from where the pure water without algae is used as a circulating water to cool condenser 14 and absorb CO_2 in 16. Wet organic matter is dried in 18 by heat of flue gases . Relatively dry fuel is directed to the fluidized bed combustor 8. After combustion in the artificial air, (the mixture of oxygen and carbon dioxide) flue gases go in the cyclon separator 20, the deflected ash is returned into the pond .CO_2 with some steam go through heat exchanger 19 and fuel drier 18 to a separation point, from where a major part is mixed with oxygen, forming artificial air for fluidizer and a minor part is directed to absorber 16 to be dissolved in circulation water and returned to the pond. This minor fraction of CO_2 flow is exactly equal to CO_2 appeared in combustion. Oxygen is produced from air at the cryogenic or Ion Transport Membrane unit 10. Water from condenser 14 goes by a feed water pump through heat exchangers 18 and 19 into tubes of the fluidised bed combustor 8 (boiler). Produced steam expands in the turbine 22, driving generator. Low pressure steam is condensed in 14. Actually it is the ordinary Rankine cycle.

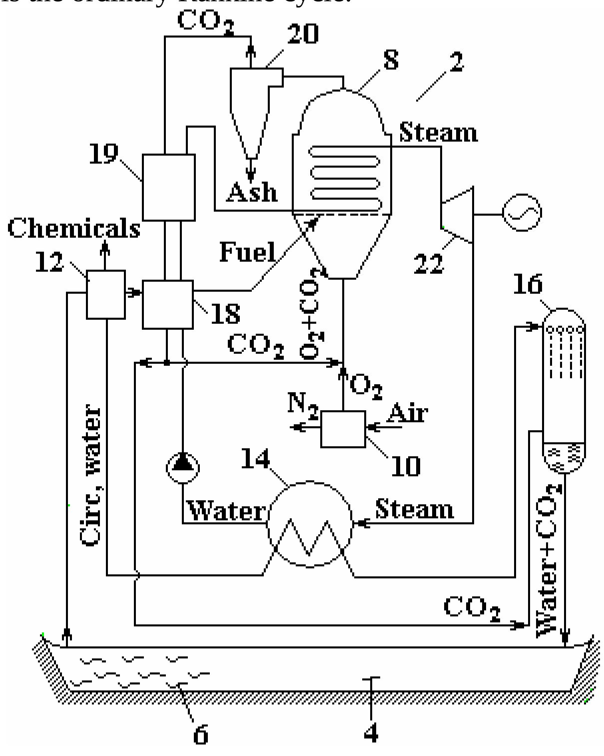
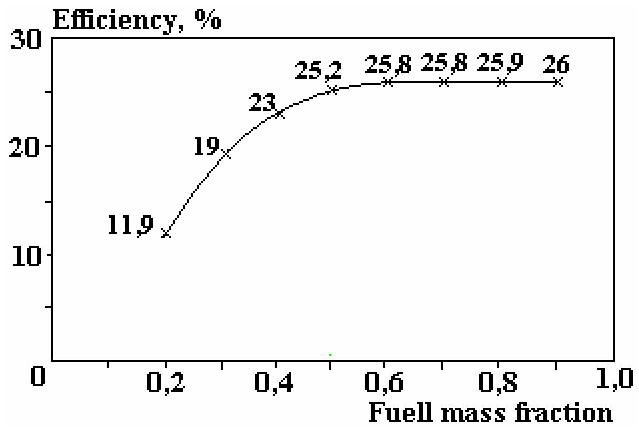


Fig.2. Schematics of the SOFT cycle [15]



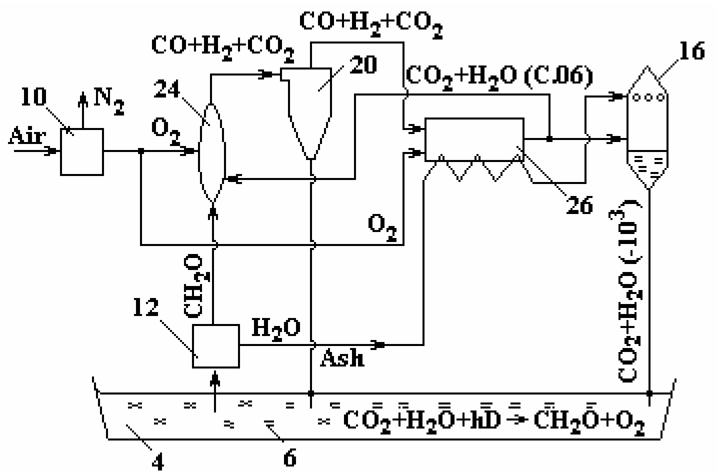


Fig. 3 and 4 from the patent description. The efficiency versus fuel wetness and a version of the SOFT cycle with fuel gasification

Some words on the chemicals production. It is unwise to combust the crude seaweed at power plant in the same sense as it is unwise such use of crude oil. A small mass fraction of seaweeds contains very useful organic chemicals which should be deflected along with water separation before the fuel combustion. There exist lots of methods of high organics separation, which is far from the scope of present paper. In any case the chemicals production could improve economics of the SOFT cycle.

Let us take for a numerical example the decentralized power supply by a small power plant of 100 kW [10]. In order to get the reliable figures we make rather modest assumptions:

- Fuel is wet (50% water content)

– ASU power consumption by 98% oxygen purity 0.22 kWh/kgO_2

– Superheated steam before turbine 130 bar, 540 ^{0}C,

– Isentropic coefficients of turbine 0.80, of feed pump 0.75.

– Seaweed productivity 16 kg/m^2 year or 10 W(th)/m^2

– Photosynthesis efficiency 4.6%.

Calculated results:

– Heat input 425.5 kW(th)

– Net output 107.3 kW (el)

– Cycle efficiency 25.2%

– Pond surface 4 ha.

The graph of efficiency versus fuel moisture see in Fig. 3. For quite possible figures of Rankine cycle with reheat and efficiency of 35% the needed surface of the pond is 3 ha. For an israelian kibbutz of some hundred people is enough only 4–5 such units and a pond of 15–20 ha. A local power plant of 10 MW by the cycle efficiency 40% and photosynthesis efficiency 6% the specific power per square meter is about 5 W (220x0.4x0.06=5.28) and pond size is about 2 km^2. By order of magnitude it is comparable with Yatir – reservoir in the desert Negev near to Beer Sheva. The Keren Kayemeth LeIsrael [11] is planning to build 100 water reservoirs in the next five years. One of these might be used for the SOFT demonstration.

Finally, for the national power demand of 10 GW (about 2 kW pro capita) in Israel a reasonable extrapolation is possible: expecting specific power of 10 W/m^2 due to increase of the cycle efficiency and photosynthesis one. It means the needed pond surface is about 1000 km^2. The surface of the Dead Sea is just the same (exactly 980 km^2). If in some future a Life sea (with the normal, not deadly salt concentration for seaweed) would appear in the desert, not too far from the Dead one, see Fig.6, it could give the country full electrical power along with lots of fresh water and organic chemicals. There would be no emission of combustion flue gases and no net consumption of oxygen, which is consumed in combustion but released in photosynthesis. The only need is solar energy and a piece of a desert. Neither terror attack could cause any serious damage.

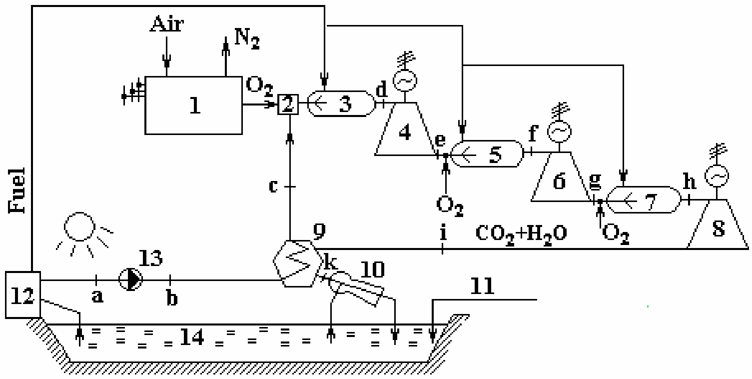


Fig. 5. First version of the SOFT cycle (1991). 1 – Oxygen plant; 2 – Steam-oxygen mixer; 3 – First combustion chamber; 4 – HP turbine; 5 – Second combustion chamber; 6 – MP turbine; 7 – Third combustion chamber; 8 – LP turbine; 9 – Recuperator; 10 – Jet condenser; 11 – Make-up water; 12 – Fuel and water plant; 13 – Feed water pump; 14 – Photosynthesis solar pond

LIFE SEA map

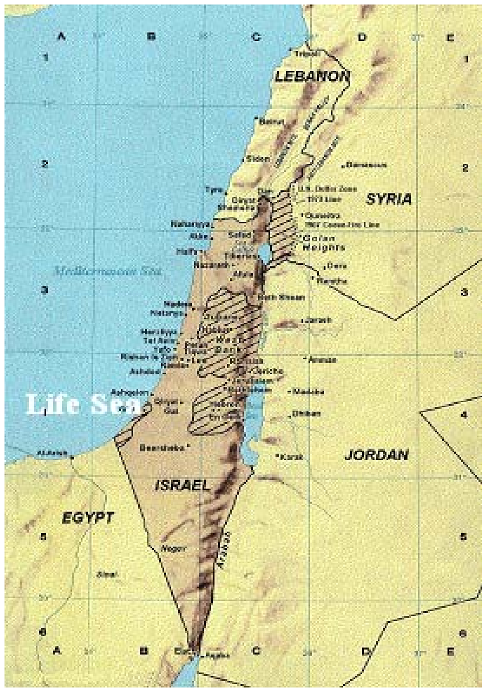


Fig. 6. Location of the tentative Life Sea in the Negev desert in the middle of the channel Red Sea – Dead Sea

An israelian representity at Johannesburg Summit, Mr Jacob Keidar announced the Israel-Jordan project of a 300 km long pipeline just from Red to Dead Seas. The Life Sea might be a useful consumer of the transferred water at the middle of the pipeline, see Fig. 6.

Gasification

In the proper energy mix not only electricity , but also gaseous or liquid fuel is needed. In the SOFT cycle it is attainable by a small modification (Fig. 3). The difference is the incomplete combustion (gasification) in the fluidised bed reactor, now it is a gasifier 24. Biomass gasification is well documented [12]. Fluidized bed gasification experiments with the sugarcane bagassa described by Gomez [13]. Produced gaseous fuel mixture consists of carbon monoxide, hydrogen and carbon dioxide. After cleaning in 20 it is used in a piston engine or turbine 26, producing mechanical power. The same fuel gas mixture might be converted into liquid fuel like methanol or even gasoline. After combustion in 26 the flue gases are absorbed by circulated water and returned to the pond 4 to feed seaweed 6.

The figures in brackets 0.06 and 10^3 reflect mass ratio water/CO_2.

Water desalination

For the state of Israel the problem of fresh water is not less severe than of electrical power supply. The annual demand is about 1.4 km^3 of fresh water. It rains only 50 days in a year and 60% of the land are deserts.

Let us consider what might the SOFT cycle do for a water desalination: is it possible to use low-grade heat after the turbine expansion to evaporate of a fraction of the circulating salty water (sea water) with the subsequent condensation of vapor for the fresh water production (desalination).

Assume an evaporator of a minor fraction of circulating water after turbine. Cooling and condensing this vapor by the major part of circulating water gives fresh water as condensat.

How large is its flowrate? Assume the turbine as of back-pressure type, by exit steam pressure 1.2 bar. If in a modern high temperature steam turbine inlet is 1000 K by 200 bar, the enthalpy is 3874 kJ/kg. After expansion the steam is at 450 K and 2830 kJ/kg. For water evaporation by 1 bar the enthalpy drop of 2500 kJ/kg is enough.

In a small power unit of 100 kW the mass flowrate of cycle water of Rankine cycle is 100/0.25.1044 = 0.4 kg/s. The mass flowrate of desalinated water is the same 0.4 kg/s.

For a small demonstration plant the figures are:

Pond surface 4 ha (40 000 m^2). Power 100 kW. Dry fuel flow 0.021 kg/s

Chemicals (4%) 1 g/s . Fresh water 0.4 kg/s

Specific dry fuel consumption is 756 g/kWh. It is about twice in excess of a standard fuel consumption in microturbine power units due to lower heating value and low efficiency.

In a 1 GW power plant with cycle efficiency 40% and pond surface 10x20 km the flowrate of produced fresh water is 4 t/s or 14400t/h. Assuming 7000 h/year operation the yield of water annually is about 0.1 km^3. It is evident, that if the SOFT cycle with water desalination would be used in full scale, it might meet all water demand. Contemporary practice of the use of18 power generating and desalinating plants at the West bank of Arabian Gulf [14] giving 15 GW of power and 1.9 km^3 of desalinated water annually, confirms above guesses. In case of applicability the experimental results of Italian researchers [16–18] with higher growth of Ulva figures, the size of mentioned ponds might be much reduced.

Comparison with the first SOFT version of 1991.

The closed cycle power plant concept, based on algae photosynthesis in a pond, combustion of organic matter of dried algae in a zero-emission power plant and CO2 capture to return in the pond for feeding algae has been published in 1991[8] see Fig.5. Here was used air separation and expansion in a steam turbine. The difference was in the inert gas, replaced nitrogen in combustor. It was not carbon dioxide but steam. Also different was algae: not mAcro but mIcro, that is why not fluidised bed combustor but the gas-turbine one as for clean fuel was assumed. After the triple expansion in turbines together with steam the carbon dioxide was returned to the pond. Now this version is actively used by Clean Energy Systems (CES) creating a demonstration plant of 5 MW in California not for algae, but ordinary gas fuel. It might be the first Zero Emission power plant. Had it been successful, it might be added by an algae fuel system for a SOFT cycle demonstration.

Conclusion

The seaweed Ulva, selected as a renewable fuel for the SOFT cycle is well documented, its main properties are : relative growth rate RGR = 0.1 -0.2 1/day (or 10 – 20 times in a month by averaged insolation) and heating value of 15 – 19 MJ/kg of ash-free dry weight. Optimal concentration of organic matter in water is about 1:1000 by mass.

The SOFT power cycle protected by U.S.Patent [15] is of practical interest to countries with sufficient solar radiation. The concept is ready for Engineering , economical calculations and demonstration. **It is non fossil fuel, non nuclear, not polluting and not oxygen consuming** power cycle with the least expensive receiver of solar radiation and effective hydrodynamic concentration of energy flow. Its additional service to human environment might be incineration by combusting Ulva with nitrides and other contaminants from added brackish water.

REFERENCES

1. *Benemann J.* Utilization of carbon dioxide from fossil fuel burning power plants with biological systems. Energy Convers.Mgmt. v.34 No9-10, p.999–1009, 1993.

2. *Alexejev V.V. et al.* Biomass of microalgae use for solar energy conversion, Techno-economic and Ecology aspects of Ocean Energy Use. TOI Vladivostok, pp.53–58, 1985 (in Russian).

3. *Brown L., Zeiler K.* Aquatic biomass and carbon dioxide trapping. Energy Convers.Mgmt.,v.34, No9-10, pp.1005–1013, 1993.

4. *Brown L.* Uptake of carbon dioxide from flue gas by microalgae. Energy Convers. Mgmt. V.37, No6-8, pp. 1363-1367, 1996.
5. *Lincoln E. Bull.* De l'Institute Oceanografique, Monaco, 12/1993.
6. *Kurano N. et al.* Carbon dioxide and microalgae. In: T.Inui et al.(eds) Advances in chemical conversions. Studies in Surface Sci. and Catalysis v.114, Elsevier, 1998.
7. *Yamada M.* Recovery and fixation of carbon dioxide. Patent of Japan 03154616, applied 10.11.1989, publ. 02.07.1991.
8. *Yantovski E.* The thermodynamics of fuel-fired power plants without exhaust gases. World Clean Energy Conference CMDC, Geneva, pp. 571-595, 4–7 Nov.1991.
9. *Osri Uri.* Seaweed cultivation project in Israel. Rosh Hanicra, 1998(private communication).
10. *Iantovski E., Mathieu Ph., Nihart R.* Biomass fuelled CO2 cycle with zero emission. Proc.Powergen Europe.Madrid.1997.
11. *Keren Kayemeth LeIsrael.* Wasser für Israel. Judisher Nationalfonds e.V. 2003.
12. *Olsson et al.* Cogeneration based on gasified biomass, Nederlands, Proc.ECOS'2000, v.4, pp.1945–1957.
13. *Gomez E.* Preliminary tests with a sugarcan bagasse fuelled fluidised bed air gasifier. Energy Conv.Mgmt.v.40,pp. 205–214, 2001.
14. *Azoury P.H.* Power and desalination in the Arabian Gulf region. Proc, Instn. Mech. Engrs. Vol215, partA, Imech E, 2001.
15. *Yantovski E.* Closed Cycle Power Plant ,US Patent 6,477,841 B1, Nov.12, 2002.
16. *M.-L de Casabianca et al.* Growth rate of Ulva rigida in different Mediterranean… Bioresource Technology v.82, March2002, pp. 27–31.
17. *Marco Bartoli et al.* Dissolved oxygen and nutrient budgets in a phytotreatment…Hydrobiologia v.550, No1, Nov.2005.
18. *Luigi Vezzulli et al.* A simple tool to help decision making…Water SA Vol.32 No4, Oct.2006.
19. *Giusti E., Marsili-Libelli S.* Modelling the interaction between nutrients and the submersed vegetation in the Orbetello Lagoon. Ecological Modelling 184 (2005) 141–161.
20. *Yantovski E., McGovern J.* Solar Energy Conversion through Seaweed Photosynthesis with combustion in a Zero Emission Power Plant Proc. Conf. Renewable Energy in Maritime Island Climates, 26–28 Apr.2006, Dublin, Ireland, pp. 23–27.
21. *Lamare M.D, Wing S.R.* Calorific content of New Zealand marine macrophytes. New Zealand Journ. Of Marine and Freshwater Research, 2001, v.35, pp. 335–341.
22. *Greertz-Hansen O., Sand-Jensen K.* Growth rate and photon yield of growth in natural populations of a marine macroalga Ulva lactuca.Mar. Ecol. Progr.Ser., vol.81:179–183, 1992.
23. *Viaroli P. et al.* Nutrient and iron limitation to Ulva blooms in a eutrophic coastal lagoon Hydrobiologia (2005) 550:57–71.

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Summary

Present paper is aimed at describing a "closed cycle" power plant schematics(SOFT, Solar Oxygen Fuel Turbine) with macroalgae (seaweed) cultivation in a pond, combustion of its organic matter in a fluidized bed boiler of Rankine cycle and return the combustion products to the pond to feed algae. Used for combustion oxygen is released to atmosphere in photosynthesis. It is further elaboration of the paper in ECOS2005 in Trondheim. As a renewable fuel the seaweed Ulva lactuca is selected. Its growth rate from many experiments (in literature) is 0.1 – 0.2 1/day, heating value of dry weight is 19 MJ/kg, optimal concentration in salty water 1:1000. Energy efficiency is less than in Photovoltaics but energy expenditures to construct the pond as solar energy receiver are much less, it gives some economic benefits. For a power unit of 100 kW the pond surface is about 4 hectare. The cultivation of seaweeds in sea water ponds is well developed in Italy and Israel either for water cleaning or chemicals production. Construction in some future of a SOFT system near to the Dead sea in Israelian desert would provide the country with needed power, chemicals and fresh water on account of solar energy. The system is protected by USPat 6,477,841 B1 of 12.11.2002 with priority in Israel of 22.03.1999. In the paper is highlighted much more benefits to customer, than in the patent text, including fresh water by desalination. In view of the active work in Italy on water cleaning due to Ulva using contaminants in water as nutrients with increase of biomass productivity the additional target of the SOFT cycle might be incineration. Some guesses of a desert surface for a massive scale use of ponds are given.