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Hydrogen from Stormy Oceans

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1. Introduction

The recent nuclear accident of Fukushima, Japan, which has hit a highly industrialized and technically advanced country, as a consequence of a natural disaster, has significantly altered worldwide opinions on possible energy strategies for the future. For many decision makers nuclear energy was a feasible large scale technology for bridging the time until cheap sustainable energy would be available sometime in the future. The advanced technology of nuclear energy and the high energy density generated convinced them in spite of the fact, that no safe solution is still available for handling radioactive waste and that the availability of uranium is limited. Now the prospect of operating up to 20.000 nuclear reactors on earth to provide a reasonable contribution to the world`s huge energy consumption (estimated 45 TW, terawatt, by the end of this century) is frightening many people. Highly developed countries like Germany, Swizzerland and Italy have already voted to search for an energy future without nuclear energy. This, however, poses a significant challenge. The development of sustainable energy sources must proceed in a much more aggressive way. And there is the question, whether highly subsidized solar technologies like photovoltaics can be preferred choices on a shorter term in a massive effort towards clean energy. Industrialized countries may be able to afford such subsidized energy, but poor countries are not. And what the industrialized world mostly needs are sustainable fuels for transport and chemical industry. What would be the most efficient and the least costly path towards a sustainable energy economy?

The author has recently studied this question and came to the conclusion that industrial society should make a bio-mimetic, or bionic approach for solving its energy problems (Tributsch 2011). Living nature has not only adapted an originally hostile climate of our planet to favourable living conditions. It has also succeeded in supplying to living beings both abundant fuels and chemicals in an entirely sustainable way. The strategy adopted was to split water with solar light, but then to attach the liberated hydrogen to a carbon containing energy carrier, carbon dioxide. Starting from the resulting carbohydrates all needed fuels and chemicals could be synthesized in an entirely sustainable way.

It is true that at present we do not have the technology to split water directly with light using a suitable catalyst. But we could use other technological strategies such as electricity generated from wind and other sustainable sources to produce hydrogen from water. Only gasified biomass is presently available as a sustainable carbon containing molecular carrier

and this resource is limited so that artificial techniques for biomass generation will be needed in the future (Tributsch, 2011). Using Fischer –Tropsch synthesis pathways, hydrogen may be combined with gasified biomass to yield any type of carbon containing energy carrier or chemical.

From such biomimetic considerations on energy technologies it became clear that an abundant supply of cheap hydrogen is the real bottleneck for a future worldwide sustainable energy economy. Today hydrogen is produced from methane. Photovoltaic and wind electricity for water splitting to obtain hydrogen is still too expensive for commercial applications. If cheap hydrogen would be available, affordable sustainable carbon based fuels and chemicals could also be produced. A key advantage of such a fuel technology would be that all our present fossil fuel infrastructure could be maintained. This would be an enormous economic and strategic advantage. The energy infrastructure would, on the other hand, have to be changed if a pure hydrogen economy would be introduced, which would also be possible and interesting. Nevertheless, hydrogen is a technically favoured energy carrier. It is easy to handle as a gas and it is environmentally friendly. In the case of a pure hydrogen economy, however, a parallel carbon based fuel cycle would additionally be needed to supply chemical industry with carbon containing chemicals.

A recent study was published on mechanisms for solar induced hydrogen liberation from water (Tributsch, 2008). There is still significant research needed, but prospects are remarkable for this technology. Artificial model systems based on two photovoltaic cells in series for water splitting have yielded a solar energy conversion efficiency of 18 % for hydrogen generation (Licht et al., 2000). This is 36 times higher than the 0.5% efficiency reached for biomass production via three harvests during one year of sugar cane in a tropical agricultural region. And artificial light-induced generation of hydrogen would not require fertile land. Methods of photo-induced solar hydrogen generation have definitively a future.

But technologies using direct solar light for hydrogen generation are presently much to expensive because solar energy influx has a low density, 1 kW/m^2 at noon, which has to be further reduced by a factor of 5-7 because of the sun movement and the day-night cycle (to an averaged influx of solar energy of only 142-200 W/m^2). Commercial photovoltaic devices today only convert 10-15% of this energy. Wind energy systems may work day and night with favourable technical efficiency and typically operate in energy density ranges between poor wind conditions of 150 W/m^2 to good ones of 350 W/m^2 and excellent wind conditions of 500 W/m^2.

Wave energy technology is based on utilization of kinetic energy of water, which has an 800 times higher density than air. A wave of 3 m can therefore supply an energy density of 36 kW per meter of wave crest. A 6 m high wave already yields an energy density of 180 kW/m. This explains why wave energy is a potentially much more economic sustainable energy source than wind (fig. 1). Smaller and thus cheaper devices can be applied for energy harvesting. Compared to wind energy wave technology is however not yet a mature technology. It is still to be located at the beginning of a longer learning curve. Different function principles for wave energy harvesting devices are still being explored and compared. They are typically based on oscillating water columns, multi-body hinged devices, or overtopping systems, and the installations are typically located at or near the

coast to deliver energy directly via electrical cable. Problems, such as matching the resonant frequency of wave energy device to wave frequency, efficiency optimization, survivability of devices and materials in agitated sea water are still being studied. There is a lot of valuable information available in the literature on wave energy and its technology (e.g. Cruz, 2008; McCormick, 2007).

The present contribution does not aim at our present wave technology, but at identifying and discussing the most efficient and potentially cheapest hydrogen production technology via wave energy far away from coast areas in stormy oceans. Ocean regions with the highest possible energy density for wave technology will be considered in order to explore its technical and economic potential. Hydrogen generation from waves in stormy seas far away from ocean shores has, to our knowledge, not yet been considered as a technological option. But such an extreme technical situation of a stormy ocean has been selected here as a probe towards a massive new generation strategy for sustainable and economic fuel.

2. The potential of open sea wave energy

The total solar power incident on the earth has been estimated to amount to approximately 174.000 TW (10^{12} W = 1TW = terawatt). Sometimes a value of 121.000 TW is given, which considers that approximately 30% of the radiation is again reflected into space and not absorbed on the earth surface (fig. 1). For comparison, energy consumption by man presently amounts to 15 TW, with 2 TW accounting for electrical energy. This amount is more than 8000 times smaller than the solar energy absorbed on earth. By the end of the century mankind is however expected to consume approximately 45 TW, with 6 TW accounting for electric energy. Years ago it has been estimated by geophysicists that approximately 2% of the solar power absorbed on the earth surface is converted into mechanical energy of wind, waves and ocean currents. This would amount to approximately 2420 TW. Maybe up to 0.6% of the absorbed solar power could be converted into waves. This rough estimate yields approximately 726 TW, much more than mankind consumes. The Open University in GB teaches in an introduction to energy sources, that a global wind power of as much as 10.000 TW (5.7% of the incident solar energy) could be available. The global wave power was estimated at 1000 TW. (Openlearn, 2011). A power share of 300 TW is assumed to be available as kinetic energy on the earth surface by Twidell and Weir (2006). Lueck and Reid estimated the downward atmosphere-ocean mechanical energy flux to 510 TW. However not more than 10% of the energy, 51 TW, is expected to enter the ocean (Lueck and Reid, 1984).

These relatively high values for the global wave energy potential have to be confronted with specialized studies on availability of wave power. In 1976 Panicker estimated the resource of wave energy in ocean waters with a depth of more than 100 m to approximately 1-10 TW. Also Issaacs and Seymour (Isaacs and Seymour, 1973) limited the global wave power potential to only 1-10 TW. This order of magnitude was recently confirmed by a quite elaborate study based on evaluation of a huge set of data on waves from satellite altimeter and buoy data (the WorldWaves data base, Topex/Poseidon (1992-2002), Jason-1 (2002-2006)) (Mork et al., 2010). These authors estimated a global wave power potential of only 3.7 TW. The World Energy Council appears to confirm that order of magnitude by assuming a wave energy potential of approximately and exceeding 2 TW. A potential of 2 TW has already been estimated just for the global coastal wave power potential (Previsic, 2004). The

wave power potential of the open ocean must be much larger, not only because of the much larger area but also because of much higher waves and all year round wave activity close to arctic and antarctic regions (Topex Poseidon radar data).

Compared to the 121.000 TW solar energy input an estimate of 3.7 TW global wave power appears to be rather modest (a fraction of only $1.65\ 10^{-5}$). This can be shown with some very simple considerations. If 3.7 TW are divided by the surface area of world oceans (361.2 million square kilometres) a medium wave energy of only 0.01 W/m² results. If 3.7 TW would be distributed on, let us say, 5% of the sea surface, where 4-6 m waves are known to occur practically all year around (Topex/Poseidon data), an average areal energy density of only 0.2 W/m² would be obtained. Such waves would barely be visible – in contrast to the large waves in huge areas on the open sea, such as in the roaring forties.

The global wave power of 3.7 TW reported appears to be too low compared to typical near-coast wave power of 30-40 kW/m or up to 200 kW/m in a stormy open sea. A 3 meter high wave has typically a wave length of 10 m and appears with a frequency of 0.2 Hz. Its power per crest length of 30-40 kW/m would have to be multiplied by 0.13 s to reach a much lower areal wave energy density of 3.9-5.2 kWs/m² (see formula below). The power, per m² of surface area, present in form of kinetic and potential energy of the wave would thus be 3.9-5.2 kW/m². Assuming a 4 kW/m² energy density of a wave field, 250 km² would already add up to 1TW. For a commercial harvest of such an amount of power maybe an area of 1000 km² would be needed. As the global wave power distribution on the world map (for example fig. 2 of Mork et al, 2010) visualizes, immensely much larger areas show measured wave power of 30-40 kW/m (crest length) or higher. It is therefore not clear, why a global wave power potential of only 3.7 TW is obtained.

The low estimated wave energy potential in some studies also contradicts a comprehensive estimate of wind power over land and near-shore, which yields a power of 72 TW (Archer and Jacobson, 2005). Wind power over the ocean should be significantly higher.

Other approaches to estimating global wave power consider the wind energy input by calculating energy transfer to the ocean surface with theoretical models (Teng et al., 2009). With a wind energy input of 57 TW, determined for 2005, the energy dissipation in deep sea water was calculated to 33 TW, 58% of the wind energy input. Since the ocean surfaces are much larger than the land surfaces, the estimate of 57 TW may be too low compared to the 72 TW estimated for over land and near shore wind potential, cited by Archer and Jacobson (2005).

From this discussion of available information on global wave energy it may be concluded that insufficient and in part contradictory information exists and more experience is needed to reach an objective picture on the global potential of open sea wave power. On the basis of above given information and arguments it is our understanding that open ocean wave power may be of the order of 10-50 TW, much higher than the 3.7 TW estimated by Mork et al. (2010). Regardless the contradictory estimations of global wave power it can be concluded, that a significant portion of mankind's power consumption may be derived from such a sustainable energy source. It can be considered to be a concentrated secondary solar energy, mediated by inhomogeneous heat generation and evaporation processes in the earth biosphere.

3. From near coast to open sea wave energy harvesting

Wave energy technology today is an on-shore or near shore technology, which converts mechanical energy of waves into electrical energy. This electrical energy is typically supplied to the land via an electrical cable. Wave energy is, as already mentioned, still an emerging technology which is still searching for the most adapted technical devices. It is also facing problems, such as material durability and destruction of technical installations in unusually big storms. A limitation of this technology is also the choice of coastal sites, which may compete with other interests and applications. Another one is a reduced height of waves, due to typically flat water near the coast. In populated coastal regions such as in Europe, or Central and North America, where wave power plants are presently installed and operated, the weather is typically such that larger waves are only present during part of the year.

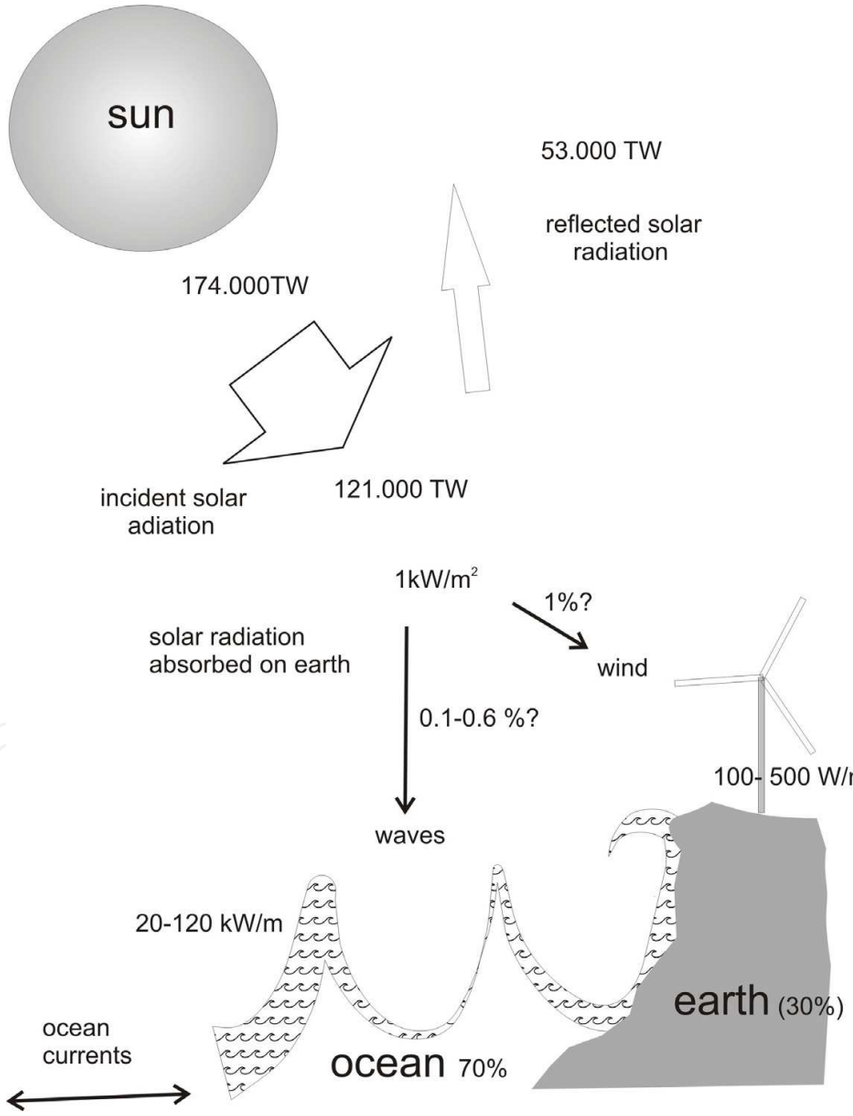


Fig. 1. Scheme visualizing solar energy input on earth and activation of mechanical energy with specification of energy densities encountered for energy harvesting

In order to get the most out of wave energy one should focus on ocean areas with very high waves, which, in addition, are present all over the year. As Topex/Poseidon and Jason-1 radar data show, such areas exist mostly north of the Antarctic continent in the roaring forties, south of Africa and Australia as well as near the southern tip of South America. Such areas of permanent intensive waves also exist close to the arctic circle. At present, there is no ocean wave project known to the author, which is aiming at energetic exploitation of these remote stormy oceans. When changing from a 3 m to a 6 m wave the energy density is increasing five-fold, but simultaneously the wave frequency is decreasing from approximately 0.2 Hz to 0.1 Hz. The resulting energy increase by a factor of approximately 2.5 has additionally to be multiplied by a factor of at least two because of the round the year wave presence in stormy oceans, in contrast to most present sites of wave energy exploitation. The approximately fivefold total increase of energy density is a good precondition for the economic feasibility of this high wave technology approach, as compared to conventional wave energy exploitation, besides of the availability of huge ocean areas for energy harvesting. But the key challenges that remain to be addressed are the survival of the wave technology in the highly stormy environment and the energy transport to industrial destinations.

In order to discuss these subjects it should be helpful to get first acquainted with some essential properties of waves as depicted in fig. 2. A water wave is a periodical phenomenon with very special behaviour. It is typically generated by wind due to the friction between air and the water surface. The mechanism of water wave generation is highly non-linear and very complex (e.g. Johnson, 1997; Falnes, 2002). Waves can develop highly divers pattern. They are, to a large extent, a far from equilibrium phenomenon and part of their properties can only be adequately understood on the basis of dynamic self organization concepts.

The distance between through and crest of a wave, as shown in fig. 2 is the wave height, while the typically used significant wave height is the average height of the highest one third of the waves in a system. The wave length is the distance between two crests, and the period T the time passing between two passages of crests. This period changes with wave height. It approximately triples when the wave height increases from 0.5 to 6 m. Simultaneously the wave length, the distance between two crests, increases from approximately 15 m to 110 m. When waves are passing, this observed kinetic movement of waves, 5 m/s to 13 m/s for the above two situations, is accompanied only by elliptical movements of water molecules (fig. 2). These movements become smaller towards the depth of the sea and practically stop in a distance of approximately a half wave length from the sea surface. In detail, a water particle moves slightly forward with the rising front of the wave, backward with the falling back side of the wave. All together the water molecule at the top of the wave only slightly moves forward as the wave passes. For 5 m high waves, which generate a power of 125 kW/m of crest length (see below), the water movements cease in approximately 45 m depth. The power obtainable from waves per unit of wave crest length is proportional to the square of wave height (Fig. 2) and follows the following formula (P = wave energy power per unit of wave crest length, ρ = water density, g = acceleration by gravity, H = significant wave height, T = wave period)(e.g. Dean and Dalrymple, 1991; Komen et.al, 1994)

$$P = \frac{\rho g^2}{64\pi} H^2 T \tag{1}$$

For a 5 m wave this power per unit crest length yields 125 kW per meter of crest length.

In order to calculate the energy density E contained per unit horizontal area, we have to calculate the sum of kinetic and potential energy of the wave:

$$E = \frac{1}{16} \rho g H^2 \tag{2}$$

Inserting (2) into (1) yields the following relation in the dimension of kWs/m²:

$$E = 1.28 \frac{P}{T} \left[\frac{kWs}{m^2} \right] \tag{3}$$

A period T of 10 s can reasonably be assumed for 5 m waves, changing relation (3) into E = 0.128 P (kWs/m²).

Taking the energy density per unit time, seconds, E/s yields the power of the wave per horizontal unit surface area. When the power, contained in a 5 m wave pattern is calculated per square meter of ocean, a value of approximately 16 kW/m² is thus found. This power can be present day and night, while the maximum solar power (at noon) is only 1 kW/m², and for a day-night average has to be divided by an additional factor of at least 5, yielding only 200 W/m². The average power content in 5 m sea waves is therefore exceeding the average available power in solar intensity by a factor of 80. This shows how much the power of weak sunlight, which is incident on earth, is finally concentrated via weather activity into the power of high waves. Via photovoltaic devices sunlight can only be harvested with an efficiency of now typically 15 %. Wave energy technology, on the other hand, aims at more than 90 % energy conversion efficiency. This may give another factor of 6 when comparing incident solar light energy with the energy present in high waves. Multiplying the 80 fold energy density per square meters of 5 meter waves by a factor of 6 yields a theoretically 480 times higher efficiency for energy harvesting.

Having estimated the power density, per horizontal area, of 16 kW/m² of a 5 m wave field we can now calculate how big the area will be that contains wave energy of one terawatt (1 TW=10^{12} W). This ocean area is 60 square kilometres only. Since only a fraction of that energy can realistically be harvested, a one terawatt (1 TW) seaborne wave power field may cover an area of 200 to 1000 square kilometres (sqkm). Let us now consider that the total surface area of the oceans in the world covers 3.6 10^8 sqkm. The violent oceans with 4-6 m waves, the southern parts (roaring forties) of the Pacific, Indian and Atlantic ocean, a large portion of the Southern Ocean around the Antarctic continent, as well as significant portions of ocean around the arctic ice cover may contribute up to 5 % of the ocean surface. That is, ocean areas with 4-6 m waves (average 5 m), which may prevail at least for a large fraction of the year, may amount up to 18 .10^6 sqkm (this can, for example, also be verified by looking at fig. 2 of Mork et al. (Mork et al, 2010) and estimating the area covered by wave power grid points with more than 40 kW/m of crest length). If 3.7 TW are divided by such

an area, an average power per crest length of only 1.56 kW/m is found, much less than the known wave power of 125 kW/m of crest length for 5 m high waves. A wave power of 1.56 kW/m corresponds to a wave height of the order of only 0.8 m. Such a simple estimation again puts a question mark to the elaborate global wave power estimation of only 3.7 TW of Mork et al. (Mork et al., 2010). The global wave power must be much bigger.

These thoughts justify the interest and promise in addressing the challenge of harvesting wave energy from stormy seas. It is the sustainable energy with the highest energy density on earth and it is abundant (excluding sporadic heavy storms, such as hurricanes). And it is localized in remote unpopulated regions of our world. Our energy hungry world would have a realistic opportunity to tap massive sustainable energy from stormy oceans, if it develops a serious effort to build up an adequate technology for harvesting it.

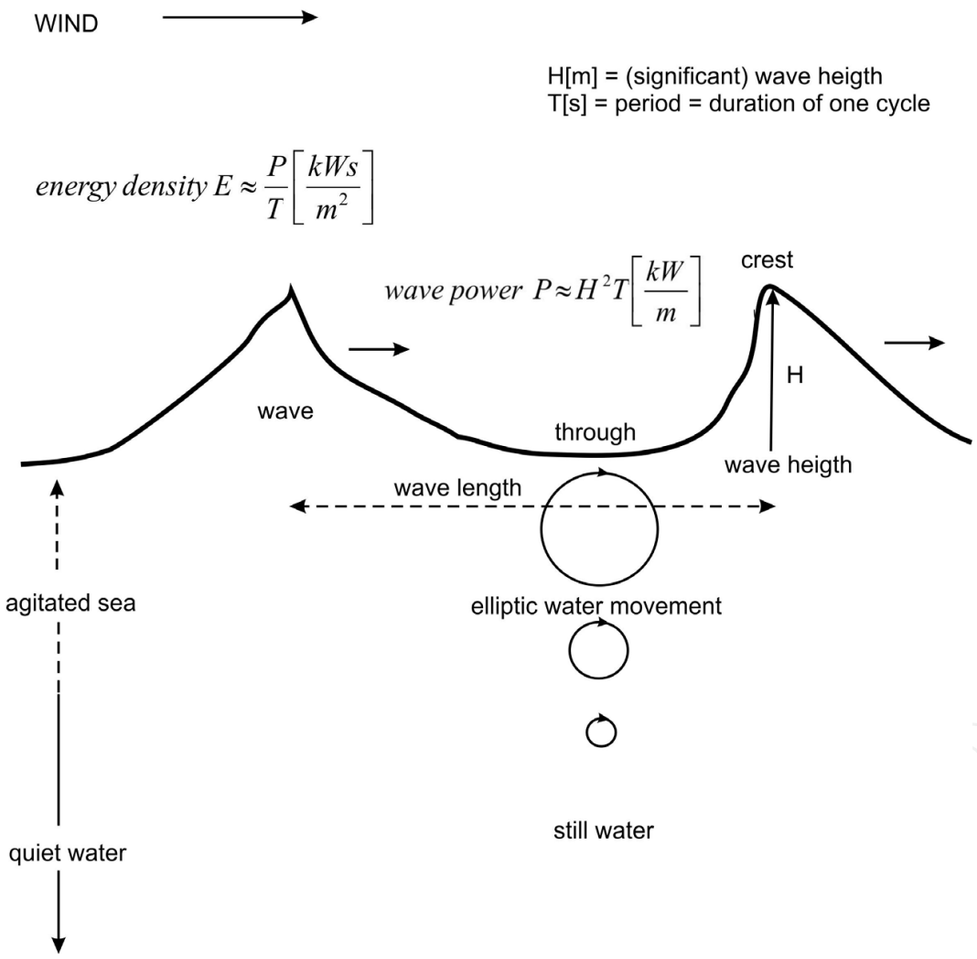


Fig. 2. Drawing which explains the physics of water waves with elliptically circulating water molecules and decreasing movements towards the depth.

4. Challenges and opportunities in stormy seas

As already mentioned, our present, emerging wave energy technology is being developed for coastal or near-coast applications. If wave technology is projected for the stormy, open

seas, several boundary conditions will change (Fig. 2). One is that in the open sea, with an average depth of 2000 to 4000 meters the wave energy installations will typically not be anchored on the ground. They will float and may be positioned via satellite and an inbuilt propagation system that uses energy gained from wave power. The second important change will be that the essential wave technological equipment will be placed under water where the wind driven wave activity is not any more felt. This will protect the technology from violent storms. Another important difference will be that the wave energy installations will be so far away from a coast that electrical cables will not be practical and economic. An energy carrying fuel, hydrogen, will directly be produced via electrolysis of sea water on site for transport in gas carrying ships or via undersea pipelines. There will be another difference to conventional near-coast wave energy installations. The fertility of open seas is known to partially be limited by the lack of structures to anchor or harbour marine species. Sunken ships have been known to become artificial reefs with abundant sea life. Large scale open sea wave energy installations may, if properly constructed, become such artificial reefs with abundant opportunities for fish farming. Such a secondary application may have a very favourable impact on economics and may, in addition address a very important emerging problem of mankind. The fish supplies of the oceans are dwindling and world population may approach 10-12 billion people by the end of this century. Developing large scale fish farming on the open sea may be a useful investment.

It will not be practical to construct wave energy installations on site in stormy open seas. Therefore, they should be constructed and finished on assembly lines on far away shipyards in order to be dropped in the sea to be assembled to a large scale energy field. Figure 3 shows and explains the structure and function of such buoys serving as elements of a large energy harvesting field. They transfer the movement of the sea waves via the mechanical forth and back movement of a piston to a large floating underwater body, where electricity is generated for hydrogen generation from water.

In order to deal with stormy oceans it is necessary to gather reliable information on wave patterns and behaviour. Waves in the roaring forties, for example, often reach 9 to 12 m high. Trains of waves of different height and shape arising from different wind patterns may combine in infinite ways. Crest and through may cancel each other and the height of a wave on one place will become equal to the combined heights of waves occurring at that place and time. As a consequence, even 15 to 24 m high waves have occasionally been observed (Hubbard, 1998).

What wave energy exploitation systems could be employed in stormy oceans? Around 65 wave energy devices are listed by Wave Energy Centre (wavec, 2011), a non profit organization for the advancement of wave energy technology. Among them are wave energy harvesting systems such as Pelamis (Ocean Power Delivery Ltd/UK), Powerboy (Ocean Power Technologies/USA), Wave Dragon (Wave Dragon ApS/Denmark), Wave Roller (AW-Energy Oy/Finland) and OEbuoy (Ocean Energy Ltd/Ireland). They include technical principles such as Attenuator Systems, Oscillating Water columns, Overtopping Devices, Oscillating wave devices, axisymmetrical point absorbers, or submerged pressure differential devices. The Pelamis system, for example, which is presently being installed in a commercial wave energy installation in Portugal, is a semi-submerged floating structure composed of cylindrical steel sections which are linked by hinged joints that contain hydraulic pumps. Oil under high pressure drives motors that power electricity generators.

Not considering the fact that hydrogen and not electricity should be the energy product from wave energy fields in stormy seas, no such system will probably survive for a long time, when the wave energy device is floating on the water surface. Powerful waves (e.g. 15 m waves with a period of 15 seconds have a power of 1.7 MW/m of crest length) will earlier or later damage or destroy them. Most conventional wave energy harvesting devices can therefore be excluded from operation in violent oceans. High waves in the open ocean should preferentially be harvested for energy with vertically moving buoys, which are positioning their essential structural and functional elements under the sea surface in the quiet water region.

This quiet region will be approximately half a wavelength below the sea level. Only the swimmer, which is following the periodic wave pattern, will approach and reaches the water surface. Such a strategy places essential existing technology outside the reach of storms. The conversion of mechanical energy via a linear generator into electricity for hydrogen evolution from water should be based on an as simple technology as possible. Delicate motors, pumps and hydraulic systems should be as much as possible avoided. Only very simple and durable technology should be applied, because service interventions on a stormy sea will be a significant challenge.

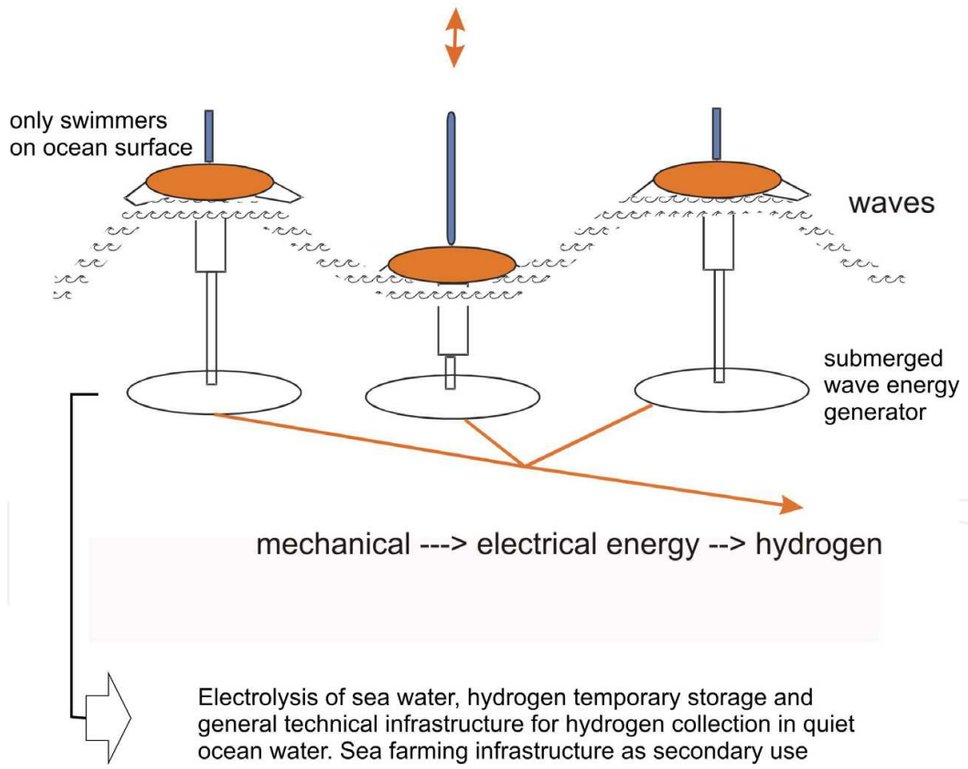


Fig. 3. Structure and function of buoys designed to harvest energy from high waves in stormy seas.

An important construction idea is to drop the buoy in such a way into the sea as to keep it afloat via the swimmer, its floating component. The main submerged body of the buoy should have such a high inertia, and additionally a high water resistance, while being

structurally linked to neighbouring devices, to keep it largely immobile and reasonably stable positioned under water. Wave activity above is periodically moving the swimmer up and down while the submerged energy converting and hydrogen generating counter structure will remain largely immobile.

The assembly of many buoys to a buoy field and its function is visualized in fig. 4. The linking together of so many structural and functional wave energy elements will provide the wave power installation with properties comparable to a submerged island over which the trains of water waves are drifting. It may be eventually positioned and propelled with an inbuilt transport and satellite navigation system, supplied by energy generated from waves.

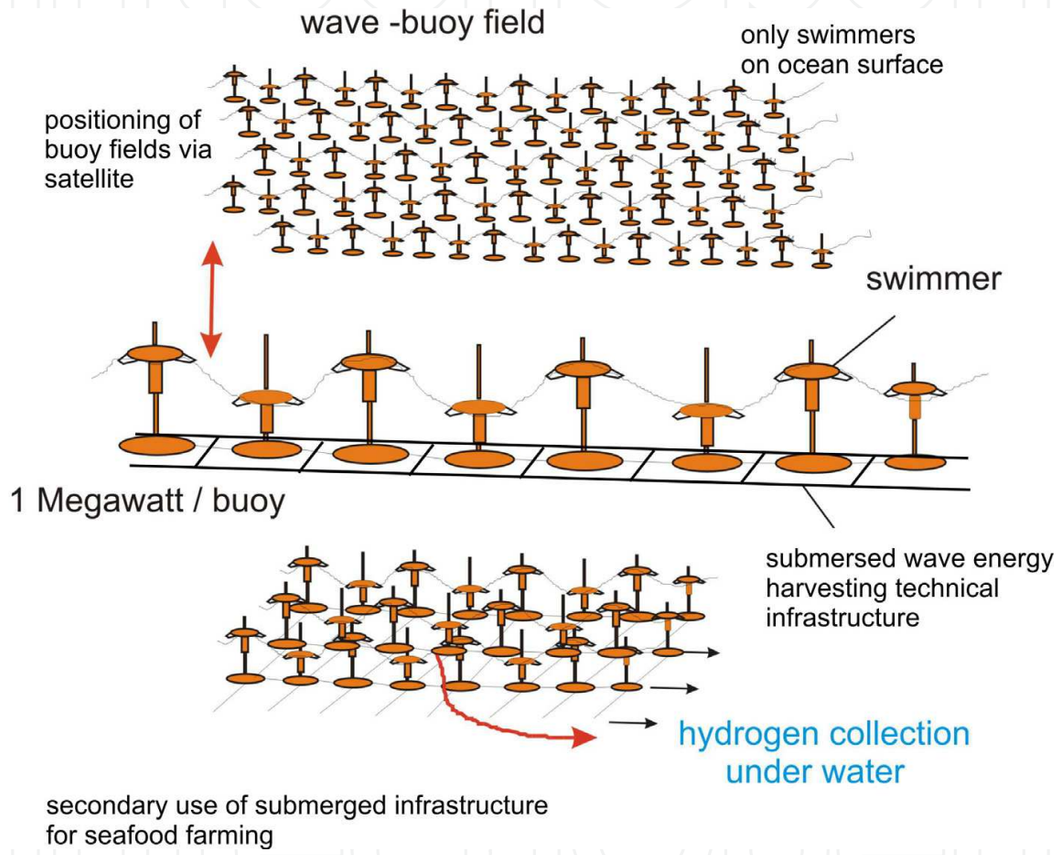


Fig. 4. Wave energy harvesting buoys could be built in mass production and assembled to large fields which could be kept in place or moved via satellite navigation. Besides of the swimmers all technical infrastructure is located in the quiet underwater region. It could also be used in a secondary way for sea food farming installations.

5. Technical infrastructure of open sea wave energy installations

When talking about mechanical under water structures and about difficulties to operate and maintain them, one should first recall what mankind has accomplished in this field. The superpowers operate fleets of sophisticated submarines. There are all kind of diving and sea floor exploring vehicles. Oil and Gas companies are prospecting for fossil fuel, constructing and maintaining production wells in many ocean regions. Under sea channels link

continental Europe with Great Britain and they are found in many other geographical locations. Ship technology has no mayor problems with stormy oceans. There is no technical excuse that could make appear a stormy ocean wave energy project a too big technical challenge for our industrial society.

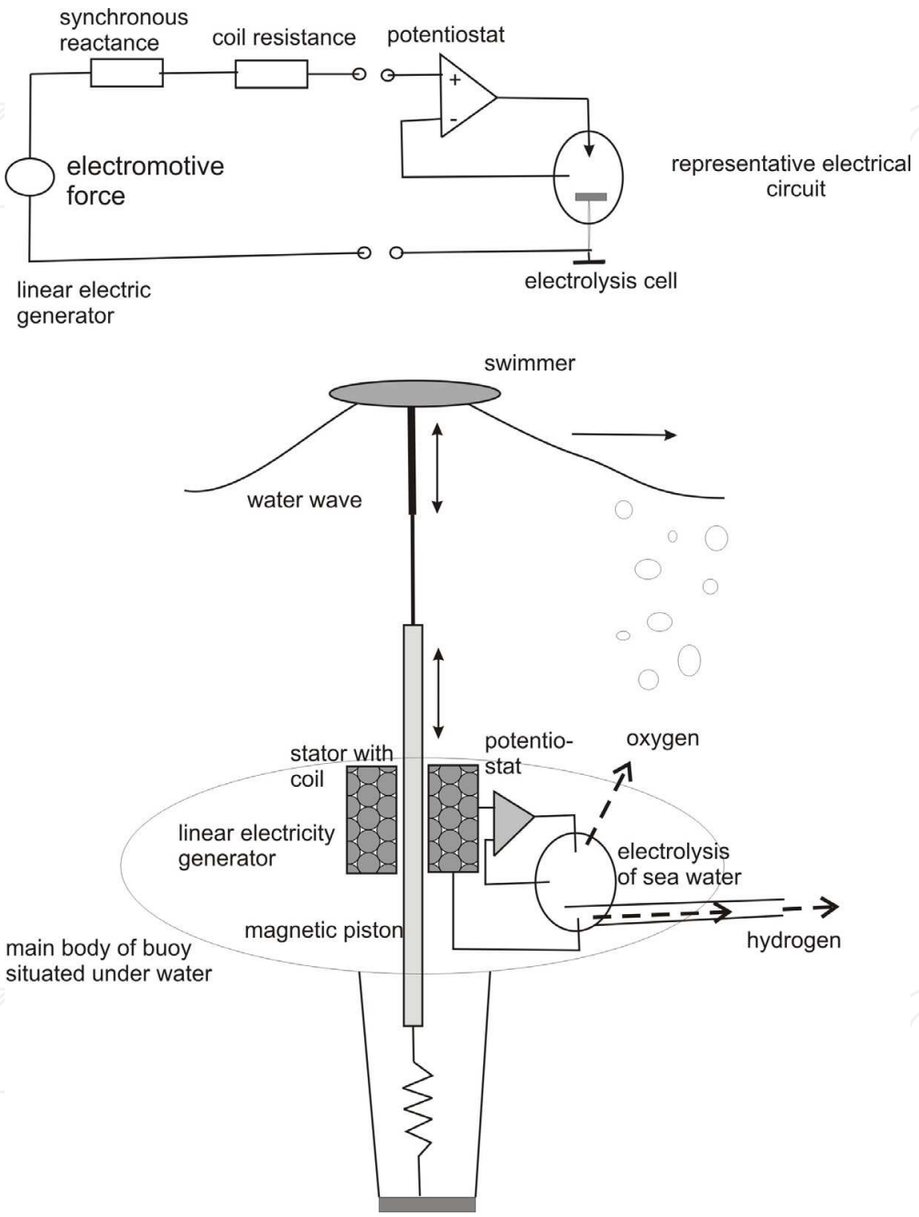


Fig. 5. Technical infrastructure of wave buoy with linear electric generator for direct hydrogen generation from sea water. Above: Representative scheme for electric circuits including linear generator, potentiostat and electrolyser. Below: structural-mechanic set-up of buoy.

Nevertheless, buoys for high waves should be constructed as simple and technically as elegant as possible, because they should be exposed to a violent and corrosive seawater

environment and servicing them would appear to be a mayor challenge and would be costly. A vertically, or better, slightly eccentrically moving buoy (because of elliptical water trajectories) should provide the simplest approach. Mechanical wave induced periodical movement could then be directly converted into direct current electricity using a linear electric generator (fig. 5). It directly converts a back and forth motion into electric energy. This is a quite well known principle and is based on the relative movement of an electrical coil and a piston of magnetic material. Is it possible to design a linear, low speed permanent magnet generator with an inherent low load angle and a satisfactory efficiency? The answer is positive and was, for example, given in a theoretical study on applicability of such an electricity generating concept to wave energy harvesting (Danielson, 2003). These calculations show, that it is possible to construct a permanent magnetic generator of 10 kW and 78,6 % efficiency with a magnetic piston moving at a speed of only 0.67 m/s. The load angle, which is relevant for efficiency was found to be satisfactorily low (10.3°). Most losses are due to heat generation through induction in copper, less in iron. Significant improvements appear still to be possible.

Another possibility to drive a linear electrical generator via sheltered underwater technology is the use of a submerged, gas filled vessel which expands and contracts under the varying ambient pressures produced by above passing waves. This principle is known as the "Archimedes Wave Swing" (waveswing, 2011). This contraction and expansion can be transmitted to a linear electricity generator. We consider this technology as more sensitive, since a gas space of changing volume has to be maintained under water for prolonged periods. In addition the efficiency will be limited via the constraints of an expanding air containing vessel, and the infrastructure will be more expensive. The linear generator found already other applications in the linear generator point absorber (Pointabsorber, 2011) and the Ocean Wave Energy Web system (oveco, 2011).



Fig. 6. At the coast wave formation and propagation is frequently affected by geological features of the environment. The transition from a near coast wave energy technology to a deep sea violent ocean wave energy technology will multiply the available power and open up huge ocean areas for sustainable energy harvesting. Instead of electricity hydrogen will become the energy carrier.

All complex electric-electronic infrastructure to produce electricity of well defined quality for hydrogen evolution from sea water in a linear generator wave buoy should be avoided (fig. 5). Instead, the direct current from the linear generator should immediately be provided to a simple potentiostat, that controls the electrical parameters of the electrolysis cell, and passed through suitable cathodes for hydrogen production from sea water (see also below). The hydrogen would be produced under pressure of several bars, depending on the depth in which the water electrolyser is functioning. An under water hydrogen collection and distribution system would finally conduct the hydrogen to a large storage system such as a properly designed submarine vessel. From here the hydrogen could finally be transported away by ship or under-sea pipeline. Today large quantities of methane are transported this way over long distances (200 ships for transport of natural gas) and the economic conditions should not be much different for hydrogen.

The proposed reasonably simple technological route to generate hydrogen from wave energy in deep and violent oceans (fig. 5) justifies mayor efforts towards optimization of technical parts and realization of a pilot installation. As compared to waves near the coast (fig. 6), the technical parameters for energy harvesting will drastically change. By positioning most technical infrastructure in deep still water, where it floats, it will easier survive the impact of storms. And hydrogen instead of electricity transport will secure energy recovery from wide ocean regions.

6. Sea water electrolysis for hydrogen

The direct current electricity produced by the linear generator can be conditioned and transformed to be used in an electrolysis cell for decomposition of sea water. Industrial electrolysis of seawater for hydrogen generation is not an entirely mature technology. When electric current is passing through water, hydrogen is, as well known, liberated at the cathode and oxygen at the anode. The hydrogen evolution process is a simple electrochemical reaction, which does not require noble metals like platinum as an electrode. Nickel is well suited for technical applications. But oxygen evolution is a demanding four-electron transfer process. Special catalysts are necessary, which chemically bind water species during the electrochemical reaction. Typically, transition metal compound are needed to accomplish this. A quite efficient catalytic electrode is RuO_2. In presence of NaCl in the water it also efficiently evolves chlorine, which is technically applied. The problem for seawater electrolysis is that sodium chloride is dissolved in seawater and that the electrode potential for evolution and liberation of chlorine gas at the anode is not very distant from the potential of oxygen evolution from water. If conditions are not properly adjusted poisonous chlorine gas may thus be liberated in a side reaction. While the electrochemical potential for oxygen and hydrogen evolution is changing with the pH value by 0.059V per pH unit, the potential for chlorine evolution does not. It is situated at E°= +1.36 V(NHE = normal hydrogen electrode). Sea water has typically a pH value between 7.8 and 8.4 and the oxygen evolution potential is therefore approximately at E° = +0.758 (NHE). The hydrogen potential is found at E° = - 0.5472 V (NHE). Some complication arises in that in non buffered sea water hydrogen evolution is accompanied by a pH shift towards alkalinity (relation (5)), oxygen evolution by a pH shift towards acidity (relation(4).

$$H_2O \rightarrow \tfrac{1}{2}\, O_2 + 2H^+ + 2e^- \quad (4)$$

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^- \quad (5)$$

The observed pH shifts are, of course, increasing with increasing current density and decreasing with increasing agitation of the seawater electrolyte. Already after the first modern energy crisis thirty years ago J.O.M. Bockris (Bockris, 1989) in his book: "Energy Options" has precisely specified the choice of electrode materials and electrochemical conditions to get efficient hydrogen generation from sea water. If the electrodes are properly selected and adjusted respectively, then chlorine can largely be excluded. This can especially be achieved by choosing highly selective catalysts for oxygen evolution. When, for example, a manganese oxide containing material is used, then oxygen evolution at high current densities can be achieved with 99.6% oxygen evolution and less than 0.4% chlorine evolution (Izuma et al., 1998). When manganese oxide was mixed with molybdenum oxide almost 100% oxygen evolution efficiency was obtained even at high current densities of 1000 A/m^2 (Fujimura et al., 1999). Such selective materials for oxygen evolution should be intensively studied to obtain optimal electrochemical behaviour for the generation of pure hydrogen.

In this connection it is interesting to note that the microscopic and macroscopic algae in the oceans had to overcome exactly the same technical electrochemical problem with respect to chlorine evolution. They also aimed at liberating oxygen from sea water, which involves a complex 4-electron extraction from water, but had to suppress chlorine evolution, which is a kinetically much simpler electrochemical process. Nature obviously succeeded since there is no chlorine evolution problem in the photosynthetic process. And it succeeded using a molecular $CaMn_4O_x$ catalysis complex, which contains manganese, as the above mentioned technical catalyst.

Sea water also contains a series of ions, of which Ca^{2+} and Mg^{2+} can produce problems at he hydrogen evolving cathode. Proton consumption there generates alkalinity (compare relation (5)), which may lead to precipitation of $CaCO_3$ and $Mg(OH)_2$. A high turnover of fresh seawater may avoid this phenomenon during electrolysis on the open ocean.

While some more industrial progress and technical experience will be required in the field of seawater electrolysis, the main parameters appear to be under control. The technique can be handled, provided adequate medium term efforts in research and technology are initiated. A mayor practical challenge will be to build an electrolysis unit, that is sufficiently robust to work unattended and automatically for a very long time. The strategy to make also this unit as simple as possible may pay off.

7. The challenge of under water equipment corrosion and fouling

It is well known that under seawater structures and interfaces are subject to various deteriorating phenomena. They range from electrochemical and bacterial corrosion to inorganic and biological fouling processes. The last two phenomena comprise consequences of processes, during which inorganic or organic deposits form on under seawater structures. Inorganic deposits may form as a consequence of precipitations and may induce solid state and electrochemical reactions of degradation of structural material. Bio-fouling may be induced by barnacles, mussels and snails, which stick to structural under water parts and damage them by chemically degrading them. Barnacles, for example, produce an epoxy-like

glue and may even stick to Teflon. Material degradation may occur through the glue of attachment or through products of metabolism or through acids used by the organisms to condition interfaces. Traditional defences against fouling were toxic paints, fouling resistant materials or periodic mechanic cleaning procedures. Copper ions were found to keep barnacle and mussel larvae from settling. They can artificially be generated via copper anodes by applying electricity.

The skin of sharks is covered by small scales or teeth like structures so that the shark surface feels like sand paper. These scales are covered by grooves, which are oriented parallel to the propagation direction. They appear to decrease the water resistance, but also suppress the settling of marine organisms. The explanation is that the highly structured skin of sharks with scales that also flex against each other does not provide reliable anchoring areas for marine organisms. Other sea animals defend themselves against attachment by other organisms by generating slimy interfaces, which are also unsafe anchoring grounds. Sea organisms seem to distrust a slimy underground and tend to avoid it. Sea mammals like whales have a very smooth skin, which provides little roughness for anchoring. In the few remaining tiny cavities there is a gel present, which may additionally discourage the settlement of marine organisms. Among sea animals there is also the strategy to produce a highly toxic interface or frequently scale off and replace the skin. Also specialized small fish have adapted to keep skins of sea animals free of undesired colonists. They have an advantage in sharing prey with their host. There is already a good technical basis for fighting fouling processes on underwater structures and there is also a good chance that biomimetic approaches will finally yield a selection of reliable remedies against this complex problem.

8. The expected impact of cheap hydrogen

Today, hydrogen is nearly entirely produced from fossil fuel (methane) and only when electricity is very cheap, such as at very large or at remote hydroelectric stations, it is generated in a sustainable way. But generation of hydrogen from wind energy and photovoltaics via electrolysis is a process which is today several times more expensive than hydrogen generation from natural gas. This is the biggest obstacle towards a dynamic development of sustainable hydrogen technology. The expensive sustainable electricity generated within and near populated areas is more efficiently used directly. It is for this reason that the here discussed approach towards cheap hydrogen from stormy oceans will be of strategic importance. Only when cheap hydrogen will be available, hydrogen technology will become really attractive (fig. 7). Hydrogen has nearly all ideal properties, which methane has, but burns in addition to water vapour only and not to carbon dioxide, as methane does. It does therefore not negatively affect the environment by contributing to the greenhouse effect. Hydrogen can be transported via pipelines or gas containers like natural gas. When stored, however, the space above has to be ventilated. For this reason, car garages have to be specially built to avoid explosion accidents, the uncontrolled combination of hydrogen with oxygen from the air. Hydrogen is an ideal fuel for transport in down-town areas, because it keeps the air clean, as already amply demonstrated by operating hydrogen buses. But certain preconditions are needed. Because it is so light it is also ideal for air-born transport. It reduces air transportation costs, and, since only water vapour is generated, no damaging atmospheric pollution should be produced. It is well

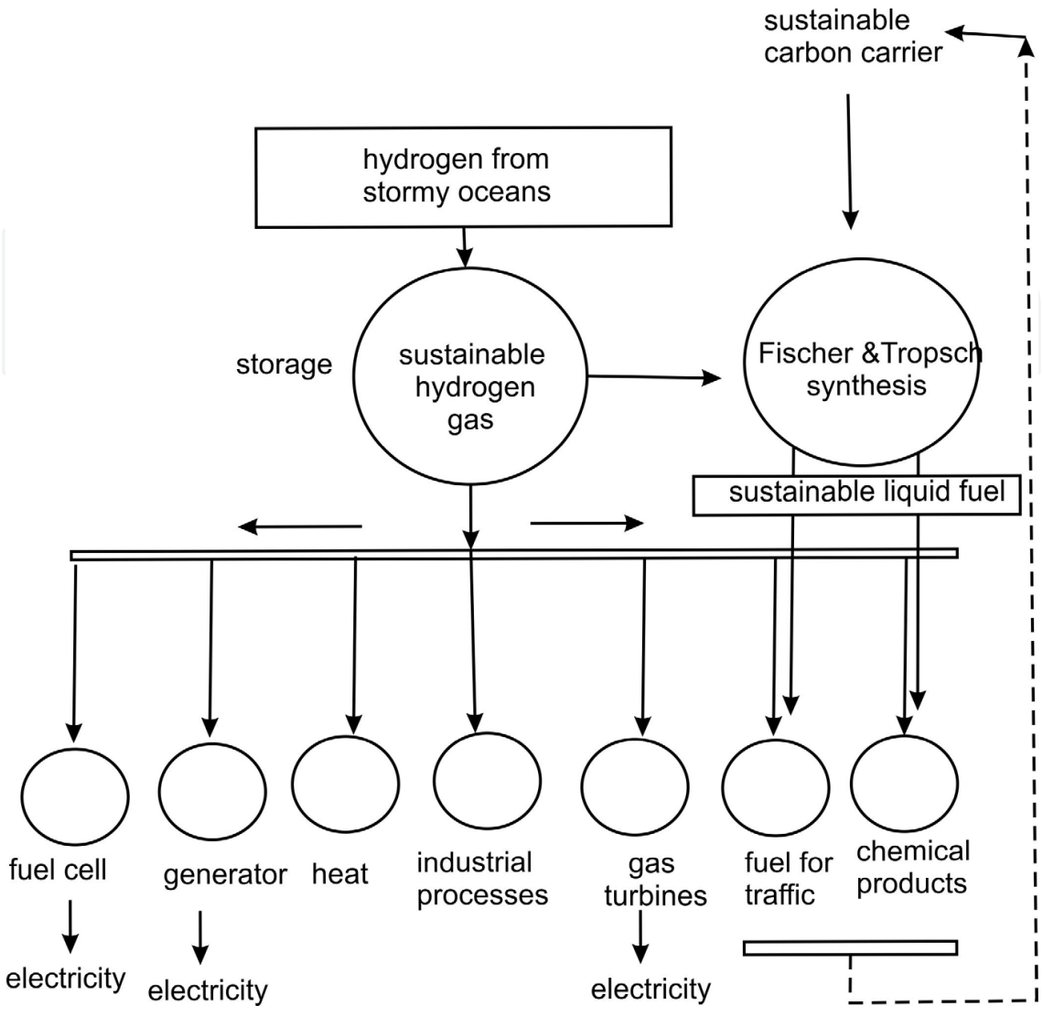


Fig. 7. Scheme explaining the use of cheap hydrogen from stormy oceans. Hydrogen can be directly used as energy carrier, but also added to a sustainable carbon containing carrier (e.g. from gasified biomass) for the production of sustainable liquid fuels

known that fossil fuel combustion by airplanes leads to the emission of tiny carbon containing aerosol nano-particles in the atmosphere. These particles act as nucleation centres for water vapour. Clouds are formed which are dimming solar light incident on our earth. Such a problematic phenomenon could be largely eliminated via hydrogen powered airplanes. Hydrogen could also replace carbon as a reducing agent in metallurgical steel production processes and it could improve and clean up many chemical processes. The advantage of hydrogen compared to carbon is that clean water vapour results instead of polluting carbon dioxide. Hydrogen could also have many applications in daily life. Instead of burning hydrogen in a flame, it could simply be made to combine with oxygen via a catalyst such as finely divided platinum nanoparticles on a porous ceramic structure. It could be used as a plate for cooking or for heating a room. Hydrogen energy could also serve as an important source of clean water in areas where water is scarce. Since hydrogen burns to water vapour, energy turnover is a source of water. For an US American energy consumer 66 litres of water would daily be produced in a side reaction. A European energy

consumer would generate approximately 33 litres of water. This is a reasonable amount, considering that the average daily water consumption in Africa is 47 litres, in Asia 85 litres. Water from hydrogen burning could become an important natural resource for population centres with high- energy consumption, as well as for the environment, where water is lacking. One big additional advantage of hydrogen is, that it can easily be converted into electricity via fuels cells. The catalysis of this reaction is comparably simple and efficient.

It has been pointed out that nature is using solar light to split water for hydrogen, but hydrogen is added to a carbon containing carrier, carbon dioxide, so that all kind of energy carriers and chemicals can be produced. On the basis of cheap and abundant hydrogen, our industrial society could follow the same energy strategy as nature. On the basis of Fischer & Tropsch catalysis hydrogen can be added to gasified biomass for synthesis of gasoline and diesel as well as of all kind of chemicals. The big advantage of such strategy is that, on the basis of such sustainable fuels, all our fuel production and distribution infrastructure could remain the same. This would be an enormous financial advantage, considering the vast amount of money, which already has been introduced into transport, conversion and distribution systems for fossil fuel. Simultaneously, however, artificial technologies for carbon dioxide fixation and biomass-generation would have to be developed, because present biomass production is not sufficient for the discussed fuel strategy and competes with food production (Tributsch, 2011).

Such advantages of hydrogen justify all efforts towards its cheap production. Generating it where the secondary solar energy reaches its maximal density (in high wave regions of the ocean), and where a huge sea area is available for modular power plant construction, would seem to be a logic strategy. The elevated energy density of high waves in combination with their availability all over the year guarantees a significant cost advantage, even if higher logistic and maintenance costs would arise.

9. Discussion and summary

Present doubts, after the nuclear disaster in Japan, whether massive nuclear energy technology could safely be handled, motivate a more aggressive development of sustainable energy. This contribution investigated the feasibility of utilizing the most dense and simultaneously most abundant secondary solar energy source, the energy of waves in stormy seas. Compared with the sunlight arriving at low energy density, 5 meter wave areas of an ocean have an eighty times higher energy density which could be harvested with up to 480 times higher energy output. This provides an immense opportunity to produce hydrogen in an economical way. An underwater technology is proposed, which is most basic in terms of infrastructure and simplicity, promising high cost efficiency and durability. A technology is discussed in which only the swimmers of buoy fields reach the water surface to periodically follow the movements of the waves. All sensitive parts as well as the main mechanical structures of the buoy fields should be positioned in deeper quiet water. The stormy wave fields would just drift over them, while periodically moving the swimming buoy elements. Challenges such as seawater electrolysis for hydrogen generation and marine corrosion and fouling of underwater structures were discussed. It is suggested that the proposed technology could be realized and optimized with adequate scientific and technological support within three decades. The cheap hydrogen produced could significantly accelerate the general sustainable development. Sustainably generated cheap

hydrogen is a key element for transforming our present mostly fossil energy economy. Added to gasified biomass it could be used to produce sustainable gasoline and diesel with the consequence that all the fossil energy production and distribution infrastructure could be maintained with significant cost advantage. Only the fuel would change from fossil to sustainable. To accomplish such a goal we have to go a courageous step towards energy harvesting from stormy oceans.

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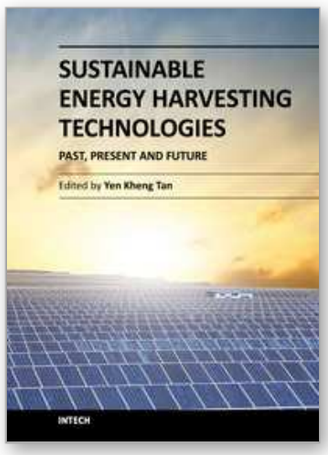
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Sustainable Energy Harvesting Technologies - Past, Present and Future

Edited by Dr. Yen Kheng Tan

ISBN 978-953-307-438-2
Hard cover, 256 pages
Publisher InTech
Published online 22, December, 2011
Published in print edition December, 2011

In the early 21st century, research and development of sustainable energy harvesting (EH) technologies have started. Since then, many EH technologies have evolved, advanced and even been successfully developed into hardware prototypes for sustaining the operational lifetime of low?power electronic devices like mobile gadgets, smart wireless sensor networks, etc. Energy harvesting is a technology that harvests freely available renewable energy from the ambient environment to recharge or put used energy back into the energy storage devices without the hassle of disrupting or even discontinuing the normal operation of the specific application. With the prior knowledge and experience developed over a decade ago, progress of sustainable EH technologies research is still intact and ongoing. EH technologies are starting to mature and strong synergies are formulating with dedicate application areas. To move forward, now would be a good time to setup a review and brainstorm session to evaluate the past, investigate and think through the present and understand and plan for the future sustainable energy harvesting technologies.

How to reference

In order to correctly reference this scholarly work, feel free to copy and paste the following:

Helmut Tributsch (2011). Hydrogen from Stormy Oceans, Sustainable Energy Harvesting Technologies - Past, Present and Future, Dr. Yen Kheng Tan (Ed.), ISBN: 978-953-307-438-2, InTech, Available from: http://www.intechopen.com/books/sustainable-energy-harvesting-technologies-past-present-and-future/hydrogen-from-stormy-oceans

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