Non-Metallic Material Science
https://ojs.bilpublishing.com/index.php/nmms

ARTICLE

Sustainability of Renewable Energy Systems with Special Reference to Ocean Thermal Energy Conversion Schemes

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ARTICLE INFO

Article history
Received: 22 August 2022
Revised : 7 September 2022
Accepted: 9 October 2022
Published Online: 20 October 2022

Keywords:
Sustainability
OTEC
SOTEC
Bio-fuel
GHG emission
Flora and fauna
Quality of life
Hydrogen
Commercial acceptability

ABSTRACT

It was required to determine relative merits of commonly used renewable energy (RE) systems for which estimation of their individual sustainability percent achievable was chosen as the single criterion assessment tool. The methodology developed for estimating sustainability included identification of individual sustainability indices (SI) and examining the scope of sustainability percent input /kWh power generation for each of SI indices and summing them up estimating total sustainability accrued from respective RE systems. The RE systems studied included photo-voltaic (PV) cells, bio-fuels, on-shore & off-shore wind energy and OTEC schemes. Coal power plant being commercially viable was studied as the referral energy scheme. Nine SI indices identified for study included resource potential, greenhouse gas saving, influence on flora & fauna, effects on human health, land loss aspects, food and potable water security, economy evaluation, and improvement in quality of life from economic growth. Total sustainability achievable showed the highest in OTEC, followed by wind, bio-fuels and PV, respectively. SI index on quality of life showed RE schemes like OTEC & bio-fuels competing equally with coal power plant having poor sustainability with the least power generation cost; whence Hybrid OTEC showed the highest sustainability with high power production cost. Four fold approaches have been suggested for reducing power generation cost of OTEC. (i) Adopting economically viable scheme of not less than 40 MW. (ii) Heating up the working fluid with solar irradiation, terming SOTEC scheme. (iii) Saving cable laying cost, from hydrogen production utilizing the power generated. (iv) Hybridization of OTEC scheme.

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DOI: https://doi.org/10.30564/nmms.v4i2.5023

1. Introduction

Energy use has been identified with economic development and simultaneous improvement in the quality of life, which has led to its ever increasing production. Since the resource for energy production is mostly fossil fuel-based (coal, oil and gas), such unabated energy production rate is causing fast depletion of fossil fuel resources which took millions of years for its formation. The fossil fuel reserve/production ration (R/P ratio) for coal with its present rate of consumption has been estimated to be of 119 years, while this ratio for combined oil and gas is hardly 60 years [1]. Besides such fuel depletion problem, the associated emission of greenhouse gases from fossil fuels (mostly from CO_2 emission) threatens global warming with serious consequences of sea level rise and other associated environmental hazards. It has been estimated that for complete combustion of 1 ton of coal-CO_2 production would be around 2.86 tons [2]. It is with these problems in view the world summit met in 2002 and agreed upon to gradually switch over to alternate type of Energy that would be environmentally sound as well as sustainable, having scope of replenishing post use [3].

In fact, sustainability has been stressed upon in the 96th Plenary Session of UN General Assembly who took up this issues as a global strategy, and defined it as "the developmental strategy, that would be able to meet the needs of the present without compromising the ability of future generations to meet their own needs, both in respect of energy and raw materials" [4]. The guiding principle underlying it spells out categorically that:

- "Each generation should require the diversity of resource base so that it does not unduly restrict the options available to future generations.
- Each generation should maintain the planet's overall qualities so that it does not get into a worse condition than received" [4].

It may be relevant to add that not only the cost component which is coming in the way of wider commercial acceptability of RE systems, each of them has their own specific advantages and disadvantages. For example wind energy though rather cheaper but have the limitation on availability of round the clock suited wind speed for power generation. Bio-fuels though advantageous for use as transport fuel, puts pressure on agricultural land. Photo-voltaic cells though advantageous in inaccessible areas, but require large areas for their installation. OTEC plants though assures non-stop round the clock power supply and have the scope of availability of huge by products, but incurs high capital cost-though have much scope of cost reduction with improved designs. It is thus considered useful to make their gradation using a single criterion assessment tool of their sustainability percent achievable per kWh power generation.

The methodology developed for ascertaining sustainability percent achievable per kWh power generation for each of these RE schemes. The following three fold approach was pursued.

(i) Identification of the individual sustainability indices (SI) required to be studied.

(ii) Scale development of sustainability gain from zero to 100. (could have negative value also on sustainability loss issues).

(iii) Logic of assigning suitable sustainability score value to each of the SI indices, where from total sustainability of the individual RE scheme can be made adding up the SI score values over each of the SI indices.

The RE schemes thus studied are as below.

1) Solar photo-voltaic cells (PV cell) which can generate electricity tapping the energy of solar insolation over the earth's surface.
2) Bio-fuels as can be produced from decomposition/degeneration of bio mass.
3) Taping wind energy of blowing wind.
4) Ocean Thermal Energy Conversion (OTEC) - generating electricity utilizing the temperature differential between surface ocean water (SOW) and deep sea ocean water (DOW).
5) Hybrid OTEC for examining scope of performance efficiency of OTEC schemes.

In order to meet the same it was required to spell out the individual sustainability indicators inclusive of environmental fall outs, termed as sustainability indices (SI), as well as developing the modus operandi of ascertaining total sustainability from combined effect of all the individual indices as may be accrued upon. Due weight-age values of the individual indices are also required to be assigned for each of the individual indices. Total sustainability can thus be estimated summing up the individual sustainability contribution from the identified indices, as applicable for concerned RE schemes and thereby making their ranking.

2. Identification of Sustainability Indices (SI) for Energy Systems

In 2015, the 70th session of UN General Assembly adopted 17 goals with the objective of sustainable and universal development programme with active participation of UNESCO, as shown below in Figure 1 [5].

Figure 1. Sustainable development goals of UNESCO [5].

Based on above stated issues, as well as considering the criterion for annulling the resource depletion problems and minimizing environmental hazards, besides ensuring issues like energy security, food & potable water availability relevant for RE systems in particular, the following sustainability indices (SI) could be identified for the present study. They are shown as below:

1) Scope of tapping concerned energy resource availability.
2) Scope of averting global warming from saving of GHG emission/carbon foot print..
3) Species (flora and fauna) loss or gain aspects from environmental fall outs.
4) Influence over human health from land, water or air pollution, if caused.
5) Land loss caused, if any.
6) Scope of availing food security.
7) Availability of potable water.
8) Economic viability which decides the commercial acceptability of the energy system.
9) Addressing scope of improving upon the quality of life, mainly from economic growth.

Quantification of each of these indices over the individual energy schemes, can be made based on the percentage of influence accrued from each of these indices. The summation of these values would then indicate the total percentage of sustainability achievable from the effect of all these indices put together. The values could of course be positive or negative depending on favouring sustainability or annulling it. If all these indices are positive showing maximum sustainability, the total sustainability would be 100 percent. If however, all of them show nil sustainability the result would be zero. In practical cases however it would be in between zero and 100 percent. Thus we get a scale of measuring sustainability percent for an energy system, which could serve as a single criterion assessment tool in ranking different energy systems and could be also be helpful in R & D efforts for their performance improvement.

3. Assessment Modality of SI for Different Energy Systems

An important point to be noted is the weight-age factor that is required to be assigned for each of these 9 SI indices, which would depend on their relative importance, and hence must not be the same for all. In 2019 in Malaysia the RE sources (solar PV, hydro--power & bio fuels) contributed to a meager 0.6%, of the total energy production, where coal contributed to 43% of the total energy use [6]. This suggests the commercial acceptability is an important point to be reckoned with urging higher weight-age factor for economy evaluation index. Same is with GHG emission aspect threatening global warming. Food and potable water availability are also considered important indicators as stressed upon from UNESCO indices shown in Figure 1. Land loss aspect would have low priority, being of local importance only. The percentage distribution of the above stated 9 SI indices is hence assigned as below in Table 1, summation of which makes 100 percent for the concerned energy system under study.

Table 1. Assigned sustainability percentage distribution of individual SI indices

Sustainability Index	Weight-age factor	% distribution	Remarks
Energy resource	1.0	10	Moderately high
Saving GHG emission	1.5	15	High
Flora and fauna	0.8	8	Moderate
Human health	0.8	8	Moderate
Land loss	0.5	5	Low
Food security	1.2	12	Rather high
Potable Water availability	1.0	10	Moderately high
Economy evaluation	1.6	16	High
Quality of life	1.6	16	High
Total		100	Summing up % share.

3.1 Energy Resource

PV cells: Direct tapping of solar energy is done using **PV cells**, which can generate electricity when light falls on them. Though this resource is almost inexhaustible, with annual electricity production capability of 1.5×10^{18} kWh from solar radiation (more than 23,000 times the energy used by human population globally [7]), but it has the limitation of non-availability at the required site during night, requiring array of battery backup as well inverters, electricity production from PV cells being DC.

For all practical purposes hardly 9~10 hours sunshine could be available for PV cells with around 30% energy loss [8]. Despite this limitation, PV cells have a unique advantage of its ease of installation in otherwise inaccessible areas. Thus sustainability criterion on resource aspect of PV cells can be considered to reach value around 70%, mainly for its easy installation in inaccessible areas as well.

Bio-fuels: Their resource gets restricted, as they are availed at the cost of agricultural land use for the growth of agricultural feedstock biomass. These are produced from plant wastes consisting of cellulose, hemicellulose or lignin type carbon-based compound, which are the primary resource for availing such energy type [8].

Though Sabah's oil palm plantations are a large source for biomass, but biomass has better value as feedstock in export markets rather than as a fuel source. This has led to the closure of biomass-based power bio-fuel plants in 2018 [9].

Thus resource sustainability index of bio-fuel cannot be considered to be not more than 50%.

Wind Energy (both off-shore & on-shore wind farms): The exploitable good cut in wind speed is around 3~5 m/s, but should not exceed 15 m/s [10,11].The scope of availability of wind resource with such optimum wind speed - for both on shore and off-shore schemes - are however limited which is not only site specific but also time specific with seasonal changes.

Thus on the count of resource sustainability index, the on-shore wind could reach maximum 30% and off-shore having better availability may be considered to reach a value of 50%.

OTEC: Around 10 TW (10 trillion W) of power, which is nearly equal to the present global energy demand, could be met only from the available OTEC resources, without affecting the thermal structure of the ocean [10]. Of course this heat input from radiant energy of the sun is maximum in equatorial region of the ocean surface which gradually lowers down, towards the polar zone. It has been estimated that 60 million sq. km. of tropical seas absorb solar radiant heat energy equivalent to 250 billion barrels of oil [11].

It may also be pointed out that due to high specific heat of water, ocean surface temperature does not meet any change during night time and exploitation of electricity from OTEC can be available 24*7 round the year with its capacity factor 95%.

Thus in all types of OTEC schemes resource sustainability index can be said to reach minimum value of 90%.

Coal based power plant: In order to compare sustainability of RE systems, a coal based power plant may be considered from resource depletion aspect taking time line to be of a millennium. In that case R/P ratio of coal with 119 years may be considered to attain hardly 12% sustainability.

Based on the above discussions, the sustainability on resource tapping aspect for all the energy systems is compared in Table 2 given below.

Table 2. Sustainability percent on resource index for the energy systems

Energy systems/ Sustainability	Sustainability% allotted for the resource index	Sustainability % of the energy systems	Sustainability % on its resource index share
PV solar	10	70	7
Bio-fuels	10	50	5
Wind on shore	10	30	3
Wind off-shore	10	50	5
CC-OTEC	10	90	9
Hybrid OTEC	10	90	9
Coal plant	10	12	1.2

3.2 Averting Global Warming by Restricting Green House Gases (GHG)

The greenhouse gases mainly responsible for global warming are CO_2, CH_4, NO_2. It may be relevant to add that though the global warming potential (GWP) of CO_2 = 1, which for CH_4=21, N_2O=320; but for all practical purposes the emission of CO_2 is of overriding importance because of its much higher emission rate in RE operations, compared to other gases [12].

Unlike fossil fuels, the scope of CO_2 emission in RE systems though virtually nil during their operational stage, but they may pose some environmental burden during their construction phase (being carried out using conventional fossil fuels). Hence, it becomes imperative to make life cycle analysis (LCA as per ISO 14040-14044 standard) of them, right from the extraction stage of the raw materials involved till their installation and dismantling, termed 'cradle to be grave operation' [13]. Emission of CO_2 thus estimated for RE systems operation, may then be compared with emission of CO_2 from a coal power plant for ascertaining its sustainability percent gain considering coal plants sustainability loss to be of 100%. Emission of CO_2 from LCA studies of a typical coal power plant has been reported to be of 900 g/kWh [14].

Sustainability percent of the RE system = CO_2 emission % saved/kWh, compared to coal plant.

A typical coal plant's CO_2 emission has been reported to be 900 g/kWh [14], and let the CO_2 emission from the concerned RE system estimated from LCA studies be = g_x/kWh.

In that case considering 900 g/kWh to be of 100% emission, g_x/kWh would be= g_x/kWh*100/900 percent emission = emission percentage/kWh of that RE system.

CO_2 emission percent saved/kWh from that RE system compared to coal would obviously be (100 - g_x/kWh*100/900), which is the sustainability percent/kWh of the concerned RE scheme for the SI of "GHG saved".

Solar PV: In case of solar PV CO_2 emission/kWh may vary between 23 and 44 g/kWh [15], the mean value of which around 30 g/kWh, is being considered for sustainability assessment in the present study. Thus sustainability percent of PV cell on this count would be:

100-30*100/900 = 96.7%

Bio-fuels: CO_2 emission/kWh of bio-fuels vary between 25 and 93g/kWh, depending on biomass feedstock used [18], the mean value of which around 60 g/kWh is considered in the present study, for assessing sustainability percent achievable.

Thus sustainability percent of bio-fuels on this count would be = 100-60*100/900 = 93.3%.

Wind energy: CO_2 emission/kWh has been said to be of 9.7 and 16.5 g/kWh for onshore and offshore wind energy systems, respectively [16,17].

Thus sustainability percent for on-shore wind energy would be = 100-9.7*100/900 = 98.9%.

And sustainability percent for off-shore wind energy would be = 100-16.5/100 = 98.2%

OTEC schemes: It could be shown from hypothetical case study of 100 MW OTEC, that CO_2 saving percent for a hybrid OTEC system would be more than 97 percent [20]. But it is to be taken note of that all types of OTEC plants can hugely increase oceans capacity of CO_2 consumption, from the burial of increased growth of marine bio-species, due to upwelling of deep ocean water, from increased growth of planktons, which is the food web of bio-species. This phenomenon, known as sequestering of CO_2 is analogous to plantation in land for annulling global warming, by increased capability of CO_2 dissolution in ocean.

Thus all types of OTEC plants can be considered to attain 100% GHG sustainability because of its inherent capability of increasing CO_2 dissolution saturation limit of the ocean water.

Based on the above discussions sustainability percent on aspect of averting global warning from GHG saving index has been shown below in Table 3.

3.3 Flora and Fauna

The influence of RE systems over different types of flora and fauna is required to be ascertained both from the qualitative aspect as also from quantitative aspect. The former could be both positive or negative, depending on whether it favours sustainability from species growth or annuls it from loss. The quantitative aspect, which means the extent of influence caused from different types of impacting parameters of the concerned energy systems, can be decided from their degree of influence as may be caused over the concerned flora and fauna. Obviously assignment of sustainability percentage could be made from

Table 3. Sustainability percent on scope of averting global warming for the energy systems.

Energy systems/ Sustainability	Sustainability% allotted for GHG saving index	Sustainability% of the energy systems	Sustainability % on its GHG saving index share
PV solar	15	96.7	14.5
Bio -fuels	15	93.3	14.0
Wind on shore	15	98.9	14.8
Wind off shore	15	98.2	14.7
CC- OTEC	15	100	15
Hybrid OTEC	15	100	15
Coal plant	15	0	0

closer examination of the impacting parameters, indicating categorization of high, moderate or low. Assignment of sustainability percent valuations can be made accordingly.

Solar PV: It is by and large environment friendly, having no impact on flora and fauna in its overall operations. But it also does not assist in growth of them, resulting in their sustainability percent to be nil.

Bio-fuels: Bio mass source favours growth of flora and fauna with no appreciable negative effect. Thus its influence being moderately high, it can be assigned a sustainability index of +60%.

Wind energy on-shore: The collision with its rotor blade and noise of wind energy have some negative effects over the birds and bats, though it is rather minor [21]. Thus overall sustainability on-shore wind may be assigned a value of –20%.

Wind energy off-shore: Noise during its construction phase may affect the roosting and preening on species growth, which can be annulled if this period is avoided for construction. In that case, sustainability index as may be assigned could be –10%, a little better than on-shore wind.

OTEC schemes: Upwelling of bottom layer ocean water with rich nutrients would favour growth of planktons - the food web of marine species and thereby can hugely facilitate growth of fish, sea -mammals and other marine species [22].

In fact, abundant production of shell fish could be observed in the west-coast of south America, due to upwelling of bottom layer ocean water from Humboldt current [23]. It was estimated that a 100 MW OTEC plant, from its upwelling of 136 m^3/sec nutrient laden bottom layer water would yield an annual production of 25,000 tons of shell fish [23].

However, there is a caution note that arises from some possibility of uplifting certain types of harmful planktons (HABs-harmful algal bloom) as well, depending on site and seasonal variations [24]; though upwelling of cold water simultaneously, help appreciably the overall growth of marine species [25].

Keeping the above perspective in view the sustainability on flora and fauna for all types of OTEC may be considered to be not be less than 70%.

Coal plant: Acidgas emission, particulate matters and heavy toxic metals like, Pb, As, Hg- pollutes air and water bodies in the vicinity of coal based power plants [26]. These factors affect negatively all types of flora and fauna of both of land and water bodies, though being not having direct effect can be said to be rather moderate. Thus sustainability percent on this index for coal plants may be considered to be around –50%.

Based on the above discussions sustainability percent on flora and fauna index has been shown below in Table 4.

3.4 Human Health

In ascertaining influence of RE systems over human health the same yardstick and methodology of qualitative and quantitative assessment for sustainability percentage estimation could be followed.

Solar PV: There remain a possibility of air and/water pollution affecting human health mainly from the toxic metals used in the construction of solar cells (containing gallium arsenide, copper-indium-gallium-diselenide, and cadmium-telluride, and others), as well from its array of batteries and other accessories, during their disposal stage and/or if not handled properly. Construction materials of solar cells inclusive of its accessories like the array of batteries, if not handled and disposed of properly, may pose environmental or public health threats to human health from water and soil pollution [27]. However, their effect would be marginal, the volume of such material being small and not affecting during their operational phase.

Thus, sustainability on the index of human health may be considered to be around –15%.

Bio-fuels: As such it has no effect on human health. But the human waste materials having the option of get-

Table 4. Sustainability percent on flora and fauna index for energy systems.

Energy systems/ Sustainability	Sustainability% allotted for flora and fauna index	Sustainability% of the energy systems	Sustainability % on its flora and fauna index share
PV solar	8	0	0
Bio -fuels	8	60	4.8
Wind on shore	8	–20	–1.6
Wind off shore	8	–10	–0.8
CC- OTEC	8	70	5.6
Hybrid OTEC	8	70	5.6
Coal plant	8	–50	–4

ting utilized as the resource material of bio-fuels, it can be said to have rather a positive impact in sustainability on human health index, which may be assigned a value of +25%.

Wind energy: Both on-shore and off-shore wind energy have no effect on human health, whose sustainability on this index may be valued as nil.

OTEC plants: It is not only enhancement of fish growth and other marine species growth, as explained in section 3.3, influence positively human health index of sustainability; but scope of availability of various types of weeds and pigments having medicinal utility in addition to mineral rich ocean bottom layer water are hugely advantageous for human health.

The sustainability of this index for all types of OTEC, may hence be considered to attain a value of +90%.

Coal plant: Air and water pollution caused from the slag wastes from coal plants, as well as from toxic metals, acid gases & particulate matters - may affect appreciably, various types of health problems, like asthma, COPD, cancer & several other diseases [27]. Thus sustainability from this index may be considered to attain a value –70%.

Based on the above discussions sustainability percent on human health index has been shown below in Table 5.

3.5 Land Loss

Land requirement, expressed as m^2/MWh, is an important parameter which involves cost component in power generation plants, and hence is an important parameter to be reckoned with. The scale of land requirement may be set using underground coal based power plant's land requirement to have near zero value, which is 0.2 m^2/MWh [28]. On the higher side, bio-fuels minimum land requirement of 250 m^2/MWh [28], may be set as 100, which would have 100% negative sustainability.

PV solar: It requires around 10 m^2 area per MWh power production [28]. Since roofs and terraces can also be utilized, effective land area requirement may be considered to be around 8 m^2/MWh.

Following the above scale presumed, sustainability percent of land requirement for solar PV would be 3.2%.

Bio-fuels: Its sustainability, as per discussions in section 3.5 would be 100%.

Wind on-shore: Its land requirement is reported to be 1.0 m^2/MWh [28]. Thus, as per the sustainability scale developed, it would have –0.4% sustainability.

Wind off-shore: Obviously with no land requirement its sustainability loss would be nil.

OTEC schemes: All OTEC schemes (other than land

Table 5. Sustainability percent on human health index for energy systems.

Energy systems/ Sustainability	Sustainability% allotted for human health index	Sustainability% of the energy systems	Sustainability % on its human health index share
PV solar	8	–15	–1.2
Bio-fuels	8	25	2
Wind on shore	8	0	0
Wind off shore	8	0	0
CC- OTEC	8	90	7.2
Hybrid OTEC	8	90	7.2
Coal plant	8	–70	–5.6

based ones) would have nil loss of this index.

Coal plants: Unlike coal plants land pressure with underground mined coals, land pressure in case of coal plant for opencast mined coal availability are high, having a value of 5 m^2/MWh. But with the current practice of open cast coal mining with the reclamation of the excavated soil with re-vegetation and soil reconstruction post-mining, would lower this land loss appreciably [30]. Thus for all practical purposes land pressure on coal plants in general can be considered to have a value of 2.5 m^2/MWh.

Thus with the scale developed sustainability of coal based power plants may be considered to have a value of 1%.

Based on the above discussions sustainability percent on land loss has been shown below in Table 6.

Food Security: All types of energy systems indirectly helps in food growth being used in agricultural farming/irrigation and/or aquaculture/ trawler fishing etc. However, it is only the OTEC technology which have direct bearing on food growth, with enhanced growth of marine bio-species, as per discussions made in section 3.3. Bio-fuels rather have deleterious effect being grown at the cost of agricultural land. However, sustainability assessment on food growth from different energy systems are discussed below.

Solar PV: The only advantage of PV cells in food growth is its scope of availability and utilization, in even the inaccessible areas, though as such it has no effect on food growth. Thus sustainability on this system would be marginal, though positive; the value of which may be assigned as 25%.

Bio-Fuels: Bio-fuels have rather negative impact since it thrives at the cost of agricultural land though its scope of use as transport fuel finds use in tractors/fishing trawlers etc., having mixed reaction of both helping its growth and at the same time reducing it.

Thus by and large its impact on sustainability may be assigned as zero, if not negative.

Wind energy: Both on-shore and off-shore wind energy when connected in grid line may be instrumental in marginally helping indirectly on irrigational efforts etc, making a minor positive impact on food growth, whose sustainability may be assigned as 15%.

OTEC: It has been estimated that annual growth of shell -fish meat from the utilization of nutrient laden DOW from a 100MW OTEC can be around 20,000 tons. It could also be estimated that implantation of 10,000 OTEC plants of 100 MW would be able to meet the entire annual protein requirement of 2 billion people with daily intake of 35 g/day [25].

In addition to it, DOW from OTEC may be utilized for food grain preservation in cold storages, without any requirement of electricity.

Thus sustainability for all types of OTEC schemes may be assigned a value of 90%.

Coal plant: Though cheaply available power from coal, may be indirectly helpful in food growth from irrigation etc. But it has negative impact from open cast mining of coal - which affects the agriculture friendly top soil (taking few 100 years for its formation) from its excavation. This makes a negative impact on food growth.

Thus, coal plant may be said to have zero sustainability on food growth, from cancelling out of both these marginal positive with marginal negative impacts.

Based on the above discussions sustainability percent on food growth has been shown below in Table 7.

Potable water availability: WHO guide line suggested the minimum requirement of potable water would be '2 liter/capita/day', whence 50 liter/capita/day is assigned as the optimum level of water use covering all purposes [32]. In the present study we are concerned only with the scope of potable water availability, which can be availed with a cost from necessary treatments. But except hybrid OTEC scheme (or OC-OTEC) all other energy systems have no scope of its availability, nor have any negative effect either. Thus other than hybrid OTEC all other energy systems would show zero sustainability on this index.

It has also been reported that even 1MW H-OTEC

Table 6. Sustainability percent on land loss index for the energy systems.

Energy systems/ Sustainability	Sustainability% allotted for land loss index	Sustainability% of the energy systems	Sustainability % on land loss index share
PV solar	5	–3.2	–0.16
Bio -fuels	5	–100	–5
Wind on shore	5	–0.4	–0.02
Wind off shore	5	0	0
CC- OTEC	5	0	0
Hybrid OTEC	5	0	0
Coal plant	5	–1	–0.05

Table 7. Sustainability percent on food growth index for the energy systems.

Energy systems/ Sustainability	Sustainability% allotted for food growth index	Sustainability% of the energy systems	Sustainability % on food growth index share
PV solar	12	25	3
Bio -fuels	12	0	0
Wind on shore	12	15	1.8
Wind off shore	12	15	1.8
CC-OTEC	12	90	10.8
Hybrid OTEC	12	90	10.8
Coal plant	12	0	0

would produce 2 million liters of potable water/day as the by-product availed free, which obviously would cater to the need of 1 million people. Thus hybrid OTEC can be assigned sustainability of 80% on this index.

Based on the above discussions, sustainability percent on potable water availability has been shown below in Table 8.

3.8 Economy Evaluation

In order to determine the sustainability percentage on economy evaluation aspect of an energy system, it would be needed to develop a scale of attaining 100% sustainability, whose electricity generation cost (LCOE/kWh) would be the cheapest one. Such value of least LCOE can never be less than \$0.02/kWh.

Thus we get an equation as below, for determining sustainability percent of an energy system.

Economic sustainability percent = \$0.02/kWh×100)/\$LCOE/kWh

where, \$LCOE/kWh=levelised cost of electricity/kWh of the concerned energy device.

Solar PV: At Jaipur, India, it could be observed from a study of solar PV power plant of 2.5 MW capacity using SANYO HIT-215NHE5 (Hetero-junction with Intrinsic Thin layer) PVmodule having P_{max} (maximum power) of 315 watts, and operating with a capacity factor of around 35%, that LCOE /kWh at 8% discount rate with 25 years life excluding the land cost was INR 10/kWh [33] which would be = \$0.13/kWh (considering conversion rate of INR to USD).

Thus sustainability % of solar PV on economy index = 0.02*100/0.13 = 15.4%.

Bio-Fuels: Biomass feedstock should be so chosen which would not be at the cost of agricultural produce, as far as practicable; and average LCOE for bio-mass is reported to be around \$0.045/kWh [34].

Thus sustainability % of bio-fuels on this index = 0.02*100/0.045 = 44.4%.

Wind energy: Wind energy -including on -shore and off-shore schemes -got their power cost appreciably lowered from technology advancement and increased volume of use in last few decades (wherever adequate resource potential of cut -in wind speed were available), and is becoming economically acceptable, nearing the cost of fossil fuel based power plants. Such power generation cost,

Table 8. Sustainability percent on potable water availability index for the energy systems.

Energy systems/ Sustainability	Sustainability% allotted on potable water availability index	Sustainability% of the energy systems	Sustainability % on potable water availability index share
PV solar	10	0	0
Bio-fuels	10	0	0
Wind on shore	10	0	0
Wind off shore	10	0	0
CC- OTEC	10	0	0
Hybrid OTEC	10	80	8
Coal plant	10	0	0

expressed as LCOE/kWh, has been reported to be $0.042 and $0.035, for on-shore and off-shore wind farms respectively [35,36]. The lower value of the later is mainly because of its availability of higher resource potential.

Thus, sustainability % of on-shore wind = 0.02*100/0.042 =47.6%.

For off-shore wind farms sustainability % = 0.02*0.035 = 57.1%

OTEC schemes (5MW net power): Capitalcost of such OTEC plant is considered to be $300* 10^6 with spin of industries $72*$10^6$ from available by products [37].

Capital recovery factor (CRF) considering 8% discount rate with 30 years life would be

$$8(1+0.08)^{30} / [(1+0.08)^{30} - 1] =0.08827433$$

Considering 95% capacity factor, annual electricity production with 95% capacity factor:

5*95*365*24*1000= 41,610,000 kWh

Considering O&M to be 1% of leveled capital cost & taking into account the economic benefits derived from spin off industries, LCOE/kWh for OTEC plant = (Capital cost *CRF+ Levelised O&M cost - Spin off industries benefits derived)/(annual power generated in kWh) = $0.49/kWh.

Thus, sustainability % of this OTEC plant = 0.02*100/0.49= 4.1%.

H-OTEC scheme (5 MW net power): H-OTEC scheme has an added advantage of producing potable water of 2 million liter water /day for 1 MW OTEC plant. Annual potable water production as by product from the same 5 MW OTEC =5*2*10^6 *365/1000 m^3 = 3,650,000 m^3 of potable water= 3650,000 m^3/41,610,000 kWh = 0.088 m^3/kWh potable water.

Since $0.42/$m^3$ is required for producing potable water by desalination using MSF (multi-stage flash purification method of desalination of water [31], it can be considered lowering of LCOE by the same amount for H-OTEC.

Thus LCOE/kWh for H-OTEC = $(0.49- 0.088*0.42)= $ 0.45.

Thus, sustainability % of this OTEC plant = 0.02*100/0.45= 4.4%.

Coal based plants: It was reported that LCOE for a typical coal based power plant =$0.28/kWh.

Thus, sustainability % of coal based powered plant = 0.02*100/0.028= 71.4%.

Based on the above discussions sustainability percent on economy evaluation has been shown below in Table 9.

3.9 Quality Improvement of Life

It would depend on the advancement of economic prospect of the society and other social parameters like, employment generation, food availability, scope on spread of education etc. In order to make quantitative assessment on sustainability in the perspective of energy systems, it would be quite logical to consider only the following three factors, which are:

a) commercial acceptability of the energy system concerned, which is the same as its economic viability.
b) getting easy access to the energy system concerned, which is the same as resource potential.
c) other social factors like, scope of employment generation, food availability etc.

Amongst the above three parameters, depending on relative importance, parameter ‘a’, the economic viability may be assigned 40% share of its total sustainability with the other two ‘b’, and ‘c’ items with 30% share for each.

Sustainability percent of this index on quality improvement of life, for different energy systems, have been estimated based on the above stated premise of sustainability distribution pattern.

Solar PV: Its (a) economy evaluation shows a value of 15.4% and (b) resource potential (for scope of installation in inaccessible areas) to be 70%. Factor “c” having moderate scope on employment generation to some extent and having scope of implantation in inaccessible areas, it can be said to be around 50%.

Thus total sustainability on this index = 15.4% of 40 (as

Table 9. Sustainability percent on economy evaluation index for the energy systems.

Energy systems/ Sustainability	Sustainability% allotted on economy evaluation index	Sustainability% of the energy systems	Sustainability % on economy evaluation index share
PV solar	16	15.4	2.5
Bio-fuels	16	44.4	7.1
Wind on shore	16	47.6	7.6
Wind off shore	16	57.1	9.1
5 MW OTEC	16	4.1	0.7
Hybrid OTEC	16	4.4	0.7
Coal plant	16	71.4	11.4

per Table 9) +70% of 30 (as per Table 2) and 50% of 30 = 42.2%.

Bio-Fuels: Its economy evaluation shows a value of 44.4% (Table 9) and resource potential to be 50% (Table 2) and in item c) it has an unique advantage on scope of use not only as transport fuel but also of energy production from waste materials and thus may be assigned a value of 70%.

Thus the total sustainability on this index = 44.4% of 40+ 50% of 30 +70% of 30= 53.8%.

Wind on-shore: Its economy evaluation shows a value of 47.6% (Table 9) and resource potential to be 30% (Table 2) and in item c)have less scope of employment generation, which is rather marginal, around 20% only.

Thus the total sustainability on this index = 47.6% of 40+ 30% of 30 +20% of 30= 34.0%.

Wind off-shore: Its economy evaluation shows a value of 57.1% (Table 9) and resource potential to be 50% (Table 2) and in item c) have less scope of employment generation, which is rather marginal, around 20% only.

Thus the total sustainability on this index = 57.1% of 40+ 50% of 30 +20% of 30= 43.8%.

OTEC schemes (5MW net power): Its economy evaluation shows a value of 4.1% (Table 9) and resource potential to be 90% (Table 2) and in item c) have huge scope of employment generation from enhanced marine species growth (fish, sea-weeds, abalone, mineral rich treated bottom layer ocean water) and opening up scope of spin-off industries and could be considered to attain a value of 80%.

Thus the total sustainability on this index = 4.1% of 40+ 90% of 30 +80% of 30= 52.6%.

H-OTEC (5MWS Net Power): Its economy evaluation shows a value of 4.4% (Table 9) and resource potential to be 90% (Table 2) and in item c) have huge scope of employment generation from enhanced marine species growth and opening up scope of spin-off industries and as well as scope of huge quantity potable water availed free, thereby with further improvement sustainability assessment, may be around 90%.

Thus the total sustainability on this index = 4.4% of 40+ 90% of 30 +85% of 30= 54.3%.

Coal plant: Its economy evaluation shows a value of 71.4% (Table 9) and resource potential to be 12% (Table 2) and in item c) have huge scope of employment generation from power plant as well as from coal mines which is labour intensive industry; though its harmful effect on human health and facilitating global warming is an impediment in improvement on quality of life. Thus by and large its overall scoring on societal index of item c), may be taken to be not less than 70%.

Thus the total sustainability on this index = 71.4% of 40+ 12% of 30 +70% of 30= 53.2%.

Based on the above discussions sustainability percent of the index on improvement in quality of life, has been shown below in Table 10.

Total sustainability: Combined effect on sustainability of the above stated 9 sustainability indices as may be effective from each of these 7 energy systems, are shown below in Table 11.

3.10 Discussions on the Results of Sustainability of the Energy Systems

A comparative study have been made on the total sustainability achievable (all the indices combined) of the different energy systems, inclusive of commonly used RE schemes, as per data derived in Table 11, as well their scope on improving upon the quality of life with prospect of economic growth, as could be derived from Table 9 (2^{nd} column). This has been shown below in Figure 2.

Table 10. Sustainability percent on improvement in quality of life index for the energy systems.

Energy systems/ Sustainability	Sustainability% allotted on improvement in quality of life index	Sustainability% of the energy systems	Sustainability % on improvement in quality of life index share
PV solar	16	42.2	6.8
Bio-fuels	16	53.8	8.6
Wind on shore	16	34.0	5.4
Wind off shore	16	43.8	7.0
5 MW OTEC	16	52.6	8.4
Hybrid OTEC	16	54.1	8.7
Coal plant	16	53.2	8.5

Table 11. Total Sustainability percent of different RE schemes inclusive of a coal-based plant.

Energy Scheme/ indices	PV solar	Bio-fuels	Wind On shore	Wind off shore	5 MW OTEC	Hybrid OTEC	Coal plant	Data source
Resource	7	5	3	5	9	9	1.2	Table 2
GHG saving	14.5	14.0	14.8	14.7	15	15	0	Table 3
Flora & Fauna	0	4.8	–1.6	–0.8	5.6	5.6	–4.0	Table 4
Human health	–1.2	2	0	0	7.2	7.2	–5.6	Table 5
Land loss	–0.16	–5	–0.02	0	0	0	–0.05	Table 6
Food	3.0	0	1.8	1.8	10.8	10.8	0	Table 7
Water	0	0	0	0	0	8	0	Table 8
Economy	2.5	7.1	7.6	9.1	0.7	0.7	11.4	Table 9
Life quality	6.8	8.6	5.4	7.0	8.4	8.7	8.5	Table 10
Grand total	32.44	36.5	30.98	36.8	56.7	65.0	11.45	

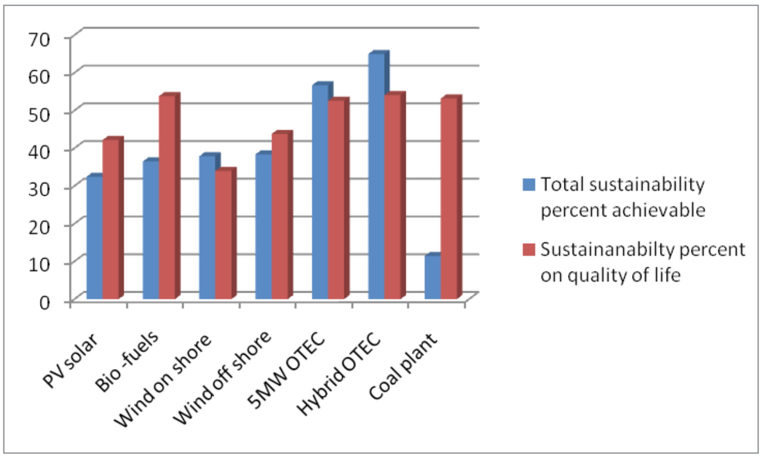

Figure 2. Total sustainability versus quality improvement of life for competing energy systems.

It could be observed that total sustainability of RE schemes shows highest value for hybrid OTEC followed by 5 MW CC-OTEC, wind (both off-shore and on-shore ones) bio-fuels and PV solar, respectively.

It was also noted from closer introspect on Figure 2, that coal plant having minimum total sustainability of less than 12% - affecting global warming, resource depletion and affecting human health, does have more than 50% sustainability on the criterion on quality improvement of life only for its commercial acceptability, unlike other RE systems with rather less commercial acceptance, though wind energy's economic viability is only a little above coal plants. But OTEC schemes, despite its low values on economic viability, competes with coal, rather better when considered its hybrid schemes, over the criterion of 'improving upon the quality of life'. Bio-fuels also shows high sustainability on this criterion like OTEC, followed by off-shore wind, PV solar & onshore wind respectively.

Thus, OTEC opens up huge scope of economic growth around its application site, with its inherent huge scope of facilitating food security, employment generation, water security besides energy security.

It is hence been considered pertinent to examine scope of cost reduction of OTEC system, so that it can emerge as a commercially viable technology as well.

4. Scope of Electricity Generation Cost Reduction of OTEC Schemes

The only limitation of OTEC is its, high capital cost involvement for installation and also poor power conversion efficiency. The following four-fold approaches are being suggested to address these problems. They are:

1) Economic assessment of OTEC from power generation cost aspect (LCOE).
2) Using heating of solar irradiation for increasing power conversion efficiency, modified as SOTEC.
3) Storing electricity generated from production of hydrogen and thus saving long cable cost and transmission loss.
4) Hybridization of OTEC schemes.

4.1 Economic Assessment of OTEC

The capital cost of OTEC varies asymptotically making its LCOE/kWh to vary according to the size of OTEC plant, as shown below in Figure 3 [40]. It would be obvious from Figure 3, that the break-even point of electricity generation cost of OTEC is around 40 MW, below which it shoots up rather sharply.

Thus OTEC scheme of 40 MW should be the minimum size for commercial type OTEC plants, where 100 MW OTEC plant shows minimum power generation cost.

4.2 Increasing Power Conversion Efficiency Using SOTEC

The power conversion efficiency in OTEC scheme is around 3-5% only, which is caused from low temperature difference (20-30) K between SOW & DOW. This makes electricity generation cost of OTEC rather high. Saga University (Japan) researchers proposed an improved OTEC scheme that would not only utilize ocean's thermal energy for its electricity production, but also solar thermal energy as the heat sources effecting further heating of the SOW and/or heating up the working fluid NH_3, and thereby increase its power conversion efficiency. This modified OTEC was termed SOTEC [41].

They proposed using low cost flat plat type solar collector for making an additional temperature rise utilizing heating effect of the sun's radiation, and thereby further warming up the SOW, termed SOTEC-1, which could also heat up the working fluid (NH_3) exiting the evaporator termed as SOTEC 2. The solar collector could thus elevate the temperature of turbine inlet fluid to an additional 20 K (>40 °C) and thereby increasing the Rankine cycle efficiency from 3.4 to 7.6 [41]. Schematic diagram of these two types of SOTEC are shown below in Figure 4.

It may be added that normally only 0.5% of water of

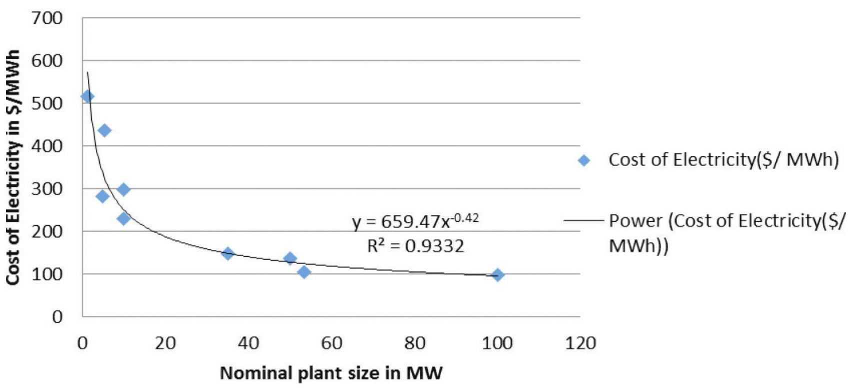

Figure 3. Cost of electricity versus OC-OTEC plant site Copyright© 2016 by Taylor & Francis

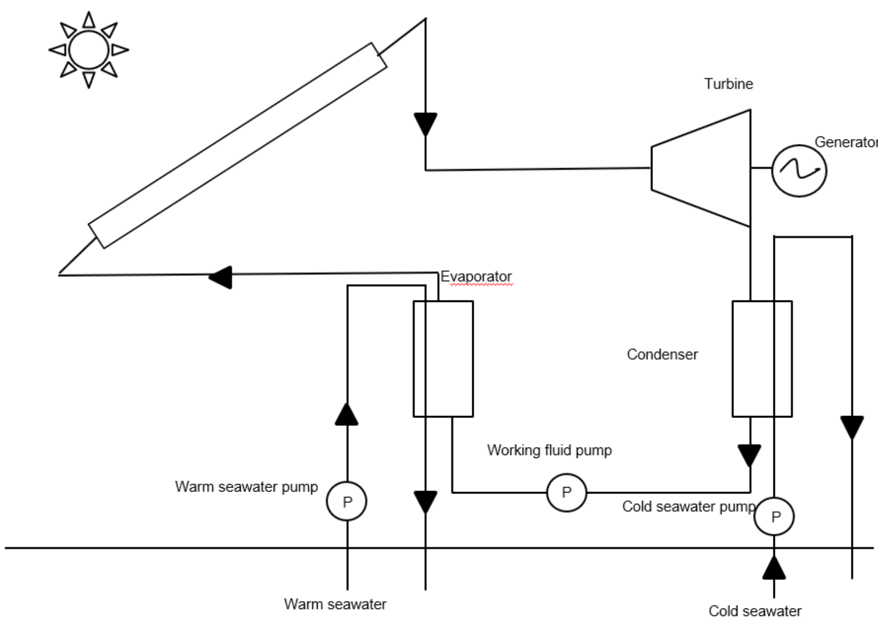

Figure 4. SOTEC-1. Schematic diagram giving the components [41].

the SOW feed gets evaporated in OC-OTEC or hybrid OTEC, since the high latent heat of water evaporation effecting cooling, stops further evaporation (Steam generation rate from SOW = Heat absorbed from SOW/latent heat of evaporation at that temperature and pressure of the vacuum chamber pressure of 0.03 bar). But with higher temperature feed of SOW is bound to make more water evaporation with additional potable water availability as well, besides increasing power conversion efficiency of SOTEC.

4.3 Hydrogen Generation from OTEC

The electricity generated from OTEC may be utilized by storing it through hydrogen production by electrolysis and thereafter converting the stored hydrogen to electricity through fuel cell route. On the other side storage of hydrogen is made converting it to hydrogen enriched product like CH_3OH, NH_3, $NaBH_4$, etc. - where hydrogen availability from hydrolysis in fuel cell could be more than the amount stored.

In order to achieve better performance of electrolysis proton exchange membrane electrolyser (PEME) has been suggested to be used [42]. It may be added that along with hydrogen there is simultaneous production of oxygen, which would be 8 times the weight of hydrogen produced.

Such storage of hydrogen utilizing OTEC generated power would not only save cost of cable line layout but would also address power transmission loss in cable line connection reaching the grid line. In fact, it has been opined that advanced 2nd/3rd generation OTEC with its huge benefits of by-products is likely to lower electricity production so cheap, that OTEC would be considered a good option opening up the scope of use of hydrogen as the future energy source [43].

4.4 Hybridization of OTEC

Hybridization of OTEC may be made by combining both the closed cycle OTEC (CC-OTEC) and open cycle OTEC (OC-OTEC) combined together, as shown in the flow-sheet diagram in Figure 5, given below. The left side showing OC-OTEC cycle would be mainly for water production, while the left one shows CC-OTEC cycle for power generation [44]. Pilot plant project of the same is going to be set up for further study by UTM research team at Malaysia.

It may be added that such hybridization may also be made combining PV solar as well as off-shore wind schemes utilizing the huge platform of large scale OTEC plant ship as well as in platforms of the spin off industries which may come up from hydrogen generation industries. The PV scheme thus installed on OTEC plant ship would save land requirement cost of PV cells. Application off-shore wind schemes over OTEC ship would lower its power generation cost by eliminating its costly foundation cost in the ocean bed, in addition to its scope of higher resource potential from availability of higher wind speed far off from shore.

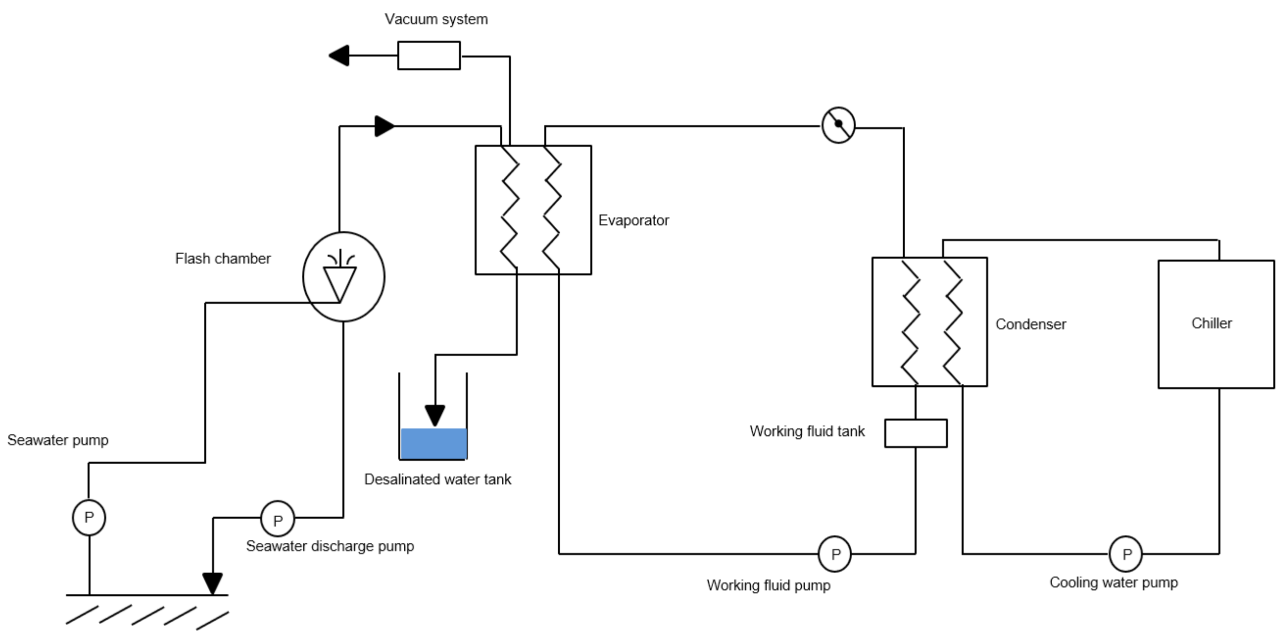

Figure 5. Basic cycle of Hybrid OTEC scheme [44].

5. Conclusions

It could be observed from the sustainability assessment study that scope of saving GHG emission for averting global warming though more than 95% from most of the RE schemes studied, but for OTEC schemes it is the best and reaches 100% mainly from sequestering of CO_2, which is an added advantage of OTEC.

As regards the potential of economic growth, ascertained from the sustainability index on quality improvement of life, OTEC can be considered equivalent to coal power plants, rather better in case of hybrid schemes, despite the inherent limitation of its higher cost of power generation with coal having the advantage of commercial; acceptability with lowest power production cost.

Coal plants are however fully unsustainable energy scheme with sustainability less than 12%. Bio-fuels and OTEC only competes with coal as regards scope on quality improvement of life is concerned with solar and offshore wind coming next in the rank, the former having the scope of application in inaccessible areas while the power generation cost of the latter is nearly at par with coal plant.

OTEC however has huge potential on the scope of cost reduction in power generation from its application of higher capacity plants (minimum 40 MW), increased power conversion rate using SOTEC and diverting its power generation to hydrogen production and thus storing electricity.

Besides energy security OTEC schemes, particularly Hybrid OTEC, provide water security food security and a host of spin-off industries.

Conflict of Interest

There is no conflict of interest.

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