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REVIEW ARTICLE

Global warming, a global energy resource

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ABSTRACT

Global warming is a thermodynamic problem. When excess heat is added to the climate system, the land warms more quickly than the oceans due to the land's reduced heat capacity. The oceans have a greater heat capacity because of their higher specific heat and the heat mixing in the upper layer of the ocean. Thermodynamic Geoengineering (TG) is a global cooling method that, when deployed at scale, would generate 1.6 times the world's current supply of primary energy and remove carbon dioxide (CO_2) from the atmosphere. The cooling would mirror the ostensible 2008–2013 global warming hiatus. At scale, 31,000 1-gigawatt (GW) ocean thermal energy conversion (OTEC) plants are estimated to be able to: a) displace about 0.8 watts per square meter (W/m^2) of average global surface heat from the surface of the ocean to deep water that could be recycled in 226-year cycles, b) produce 31 terawatts (TW) (relative to 2019 global use of 19.2 TW); c) absorb about 4.3 Gt CO_2 per year from the atmosphere by cooling the surface. The estimated cost of these plants is $2.1 trillion per year, or 30 years to ramp up to 31,000 plants, which are replaced as needed thereafter. For example, the cost of world oil consumption in 2019 was $2.3 trillion for 11.6 TW. The cost of the energy generated is estimated at $0.008/KWh.

Keywords: global warming; energy types; conversion of heat to work; heat engine; waste heat; ocean thermal stratification; carbon dioxide offgassing from the ocean to the atmosphere

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1. Introduction

Energy and climate change are inextricably linked[1]. From the first principle, the heat of global warming is an energy source like any other that can be converted from one form to another. As with all heat it always flows spontaneously from a warm reservoir to a colder one and when transferred through a heat engine, it produces work and waste heat.

The heat of global warming represents about 7% of the hemispherically antisymmetric poleward heat transport that in the northern hemisphere peaks at about 5.5 petawatts[2,3].

Since the mean solar input is 340 W/m^2, and relative to the pre-industrial benchmark the atmosphere has absorbed an extra 0.8 W/m^2 due to warming, the heat of global warming represents about 0.2% of the total solar input[2,4].

Ocean heat uptake is an essential measure of the Earth's climate. About 90% of the heat from global warming has gone into the oceans, which are becoming increasingly thermally stratified with lighter waters near the surface[5,6]. This configuration acts as a barrier to the efficient mixing of heat, carbon, oxygen, and nutrients vital to aquatic life. However, the efficient mixing of these ingredients would eliminate all risks of climate change and have the potential to produce over twice the energy currently derived from fossil fuels.

The thermally stratified ocean lends itself to the conversion of a portion of the heat of global warming to work in accordance with the First and Second Laws of Thermodynamics. However, a thermally stratified ocean resists the movement of surface heat into deep water due to buoyancy.

To induce vertical movement through a heat engine, heat pipes, which are highly effective thermal conductors that transfer heat through the latent heat of boiling and condensation of a low-boiling-point working fluid, are required.

Water is at its greatest density at a temperature of 4 °C and is universally found at an ocean depth of about 1000 m.

Heat directed through a heat engine to produce work would be a deletion of heat from the ocean because this work is undertaken on the land or at least at the ocean's surface.

In this study, the author advances the proposition; that the Laws of Thermodynamics are the only appropriate signpost for coherent climate policy.

2. The global heat engine as an archetype for anthropogenic heat engines

The oceans, constantly in motion, are the Earth's natural heat engine[7]. Although tides and waves are the obvious manifestations of this motion, the unseen bulk of this movement is driven by the push of dense brine sinking to the seafloor as surface water freezes at the poles each winter, and the spontaneous pull of warmed tropical waters seeking the poles in accordance the Second Law of Thermodynamics. This heat engine, known as the thermohaline circulation, is also known as "the global conveyor belt."

2.1. The ocean/atmosphere interface

The ocean and atmosphere are closely related dynamically. Energy transfers from the atmosphere to the mixed layer of the ocean, which drives upper ocean circulation[8]. In turn, there is a feedback of energy from the ocean back to the atmosphere that affects atmospheric circulation, the weather, and the climate.

In general, the ocean/atmospheric heat flux is due to differences in pressure. High pressures produce winds that distribute heat to low-pressure areas around the Earth's surface. And the Coriolis effect influences the east/west flow of the Trade Winds.

2.2. The heat source for the global heat engine

As shown in **Figure 1**, heat accumulates in the low latitudes and dissipates in the higher latitudes. In heat surplus, the low latitudes accumulate as much as 80 W/m^2. Whereas the high latitudes are in heat deficit as the heat accumulated in the tropics dissipates to space or is consumed as the latent heat of the fusion of melting ice. The net effect is 0.8 W/m^2 of global warming[2]. And since the Earth's surface is 510 million square kilometers (510 trillion square meters), the heat of warming was on average 408 TW between the years 1995 to 2016[9].

In 2023, ocean temperatures reached a record high of 15 ± 10 Zeta Joules (ZJ), which converts to 476 TW[10]. Which represents a 17% increase in warming over 20 years. Whereas the Mauna Loa Volcano CO_2 record for the same period shows only a 12% rise in atmospheric CO_2 content. Making it clear that global warming is more than just emissions[11,12].

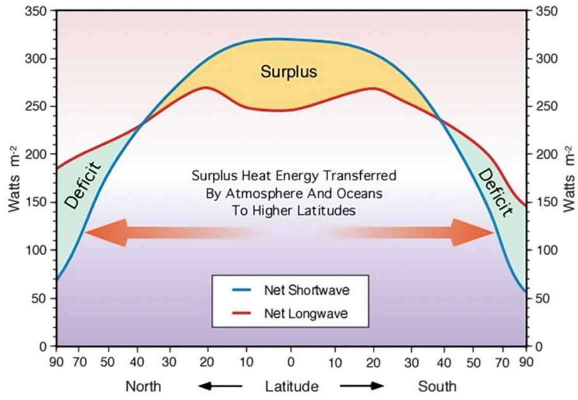

Figure 1. Heat energy transfer from surplus to deficit[13].

2.3. The heat sink for the global heat engine

The heat capacity of seawater is 3850 Joules per kilogram (J/kg) per degree Kelvin. The average seawater density is about 1027 kg/m^3 and since the volume of the ocean is 1.34 × 10^{18} cubic meters, and the mass of the ocean is 1.38 × 10^{21} kg, times 3850 J/kg, equates to an energy content of 5.3 × 10^{24} Joules/K[14].

Cooling the atmosphere by 2 °C, starting from 2050, when cooling could reasonably commence after a 25-year period of research and development, and returning to preindustrial temperatures in an equal length of time as it took for the heat to build up, and since the average depth of the ocean is about 3682 m, and the atmospheric cooling would come at the expense of ocean warming, the total ocean would need to warm by about 0.0005 °C[15].

3. The global warming resource

Global warming is a use-it-or-lose-it proposition. About 89% of the heat of warming has accumulated in the world's oceans, but it won't stay there[16].

The oceans are stratified in three layers: a surface, mixed layer that contains about 50 million km^3 of water, a middle "thermocline" that contains about 460 million km^3 of water, and the deep oceans, which contain about 890 million km^3 of water[17]. The temperature differential between the top few meters of the tropical mixed layer, which can reach as high as 38 °C, and the 4 °C of the bottom of the thermocline is the largest, potential, dispatchable source of renewable energy.

Utilizing data from the renewable energy map scenario, Hassan et al. found that renewable energy sources could command up to two-thirds of the global primary energy supply by 2050[18].

3.1. Dispatchable sources of energy

Per **Table 1**, less than 1 megawatt of the most abundant sources of dispatchable energy, TG and OTEC, are being exploited.

Table 1. The annual potential of dispatchable energies[19,20].

Technology	Annual potential in terawatts
Thermodynamic Geoengineering	31
Ocean Thermal Energy Conversion	3–11
Hydro	3–4
Biomass	2–6
Geothermal	0.3–2
Waves	0.2–2
Tidal	0.3

The thermohaline circulation, with a cycle length of between 1600 to 2000 years, ensures that sequestered ocean heat will ultimately resurface. Unless it is converted to work and the waste heat of those conversions is dissipated to space. A task that would be enhanced by the depletion of the greenhouse blanket by the production of hundreds of years of negative emissions of energy.

3.2. Heat source

Resplandy et al. produced a whole ocean thermometer based on the estimated ocean heat content, the main source of thermal inertia in the climate system, as measured by increased atmospheric oxygen (O_2) and CO_2 levels resulting from the release of these gases as the surface warms[2].

The study showed, between 1991–2016, a mean date of 2004, the ocean gained $1.29 \pm 0.79 \times 10^{22}$ J of heat per year (409 TW). Equivalent to a planetary energy imbalance of 0.80 ± 0.49 W/m^2 of the Earth's surface.

While the latest estimate of ocean heat is 476 TW[11].

3.3. Heat sink

Per **Figure 2**, the combined heat transport of the atmosphere and the ocean peaks at about 5.5 petawatts in the Northern Hemisphere and about 4.5 petawatts in the Southern Hemisphere[3]. This poleward movement of heat is the path of least resistance for heat generated in the tropics. In the Northern Hemisphere, 78% of this movement is through the atmosphere, and in the Southern Hemisphere, it is 92%, with the balance circulating through the oceans[21].

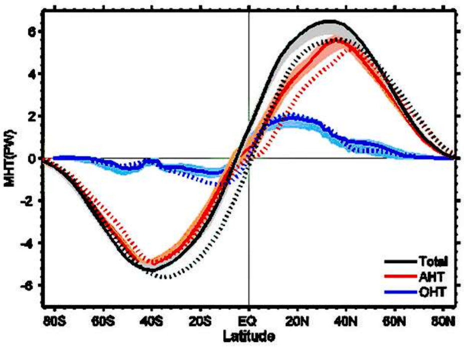

Figure 2. The heat transport of energy through the atmosphere and ocean[3].

The stored heat in the ocean will ultimately be released but at a much slower rate than it accumulates[22].

An alternative path for the heat of global warming

Figure 3 proposes an alternative route for tropical heat to reach a cold water heat sink.

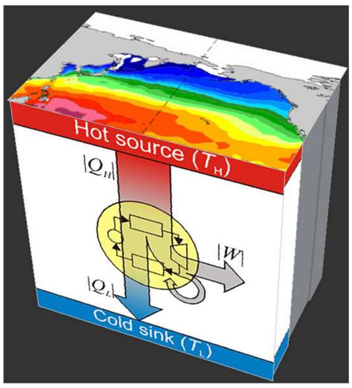

Figure 3. Surface heat transport into deep water[23].

The heat can be sent into deep water through a heat engine with the aid of a heat pipe[24]. Which is a countercurrent heat flow to the thermohaline that would extend the cycle life of the global conveyor belt and double the length of time it takes for heat sequestered in the ocean to resurface. Years that would be characterized by an absence of the ravages of global warming.

The diffusion rate of heat from deep water to the surface is 1 cm/day below the mixed layer (4 m a year) and 1 m/day through that layer. Thus, it takes about 226 years for heat released at a depth of 1000 m to regain the surface[25]. At this time, the heat unconverted to work can be recycled, 12 more times. Effectively doubling the number of years of climate respite, and the effectiveness of the oceans' heat sink.

Heat sequestered in the ocean is fungible because it represents only about 7% of the annual poleward migration of heat from the tropics to the poles.

3.4. The consequences of moving heat from the atmosphere into the ocean

The heat capacity of the ocean is about three orders greater than that of the atmosphere. The top 2.5 m of the ocean holds as much heat as the entire atmosphere[26]. Levitus et al. estimated the oceans warmed 0.09 ℃ between the depths of 0–2000 m during the period 1955–2010[27]. And proposed that if all that heat was transferred to the lower 10 km of the global atmosphere, it would be warmed by 36 ℃.

An analysis of the NOAA chart of ocean heat contact between 1960–2023 shows that from 1983 to the present, the midpoint of the Levitus study, to 2023, the amount of heat stored in the upper 2000 m of the global ocean more than doubled the 1955–2010 average[4]. The potential and inevitable heat transfer to the lower atmosphere is therefore at least 72 ℃ in a Business-As-Usual scenario where no effort is made to reduce emissions or cool the surface.

Accumulating ocean heat content is contributing to sea level rise, ocean heat waves, coral bleaching, melting of polar ice sheets and Greenland, Antarctic, and Himalayan glaciers, wildfires, droughts, more severe storms, loss of species, greater health risk, reduced food supplies, poverty and displacement, and runaway heat that will make some areas too hot for human habitation[28].

Cooling the surface, as TG would provide, would mitigate these risks.

4. Carnot efficiency

Carnot efficiency is the maximum efficiency a heat engine can attain operating between two temperatures. Improving energy efficiency is regarded as a key path to tackling global warming and achieving the UN's Sustainable Development Goals (SDGs)[29].

For OTEC, ideally, the sea surface temperature (SST) is 30 ℃ and the deep water heat sink is 4 ℃ so, with this ΔT the theoretical efficiency is about 9%.

Nihous, however, introduced the concept of a heat ladder for OTEC, in which only half the available heat produces work in the OTEC turbine, 1/16th each is lost at the evaporator and condenser pinch points, and 3/8th each is lost in the evaporators and condensers[30].

OTEC parasitic pumping losses are influenced by power capacity, pipe type, cold water discharge, and cold water depth, but they are typically assessed at between 20% to 30%. Therefore, in ideal conditions, OTEC has a thermodynamic efficiency of about 3.6%.

Melvin Prueitt, a Los Alamos Labs theoretical physicist, however, devised a system that uses a deepwater condenser and heat pipe (he called a heat channel), and calculated the efficiency of his system, using ammonia as the working fluid, at 7.6%[31]. This was for a surface temperature of 27.5 ℃ rather than the 30 ℃ TG can attain due to its ability to seek out the ocean's highest SSTs.

This considerable improvement over conventional OTEC was produced by cutting the losses through the heat evaporators and condensers by half by using hot and cold water contiguous to the heat exchangers, rather than pumping cold water from a depth of 1000 to service condensers at or near the surface. But the biggest difference was the 5.3 °C temperature gain of the boiled working fluid vapor under the gravitational influence of a 1000 m long column of gas situated vertically in the ocean.

Prueitt calculated the parasitic pumping loss of his system at only 10%[31].

Manikowski proposed CO_2 OTEC with an estimated 7% system loss compared to an ammonia working fluid, offset by a 2% pumping gain due to the proximity of the density of the gas in its gaseous and liquid states[32].

The operating temperature of a CO_2 OTEC system would approach the critical point of CO_2, 31 ℃, and the 73.8 bar pressure, in the evaporator. Which would be exceeded at a depth of 1000 m due to the gravitational influence. However, since half of the heat of the system is lost through a turbine, a gas-to-liquid phase would occur within the turbine, which would tear up the equipment.

It would therefore be necessary to operate a CO_2 OTEC system below its critical temperature and pressure. Nevertheless, subcritical CO_2, turbines would be smaller, more efficient, and less costly than typical Rankine Cycle turbines of similar capacity. And CO_2 would be a more environmentally friendly working fluid than ammonia.

5. Exergy efficiency

The conventional wisdom is that OTEC is an irreversible system. Its exergy efficiency is defined as the ratio of the thermal efficiency of the system compared to the idealized Carnot efficiency. But with TG, 7.6% of the heat of warming is converted to work, and 92.4% of the heat, which, under normal circumstances would be considered waste heat, becomes a new input for another heat engine in 226 years. As soon as the original heat returns to the surface. This process is repeated 12 more times until all the heat of warming has been converted to work and the waste heat of those conversions has dissipated into space. Since it is estimated that somewhere between 20% to 50% of energy inputs are lost as waste heat in the form of exhaust gases, cooling water, and heat lost from hot equipment surfaces and heated products, only between 6 and 16 TW of the current warming of 476 TW would ever become true waste heat[11,33]. This makes TG, at between 96.6% to 98.7% efficient, the closest thing to a reversible process as can be found in nature.

6. Waste heat

Many engineers consider the heat of warming to be waste heat in view of the low efficiency of OTEC, which is the only technology that attempts to harness the diffuse heat of warming[1]. They have more experience with and are more comfortable working with energy inputs with efficiencies in the 50% to 80% range and at high temperatures.

They equate thermal efficiency with capital efficiency, but the waste heat of nuclear power is higher than that of coal or other fossil fuel-fired plants[34].

Waste heat can be used to heat homes and industry during winters, but in summer, heatwaves in 2003, 2006, 2015, and 2018 forced the shutdown of or curtailment of the output of nuclear plants. And escalating global warming can only exacerbate the waste heat problem[35,36].

Fusion produces temperatures of about 100 million degrees Kelvin and is considered energy's holy grail[37]. Its efficiency in energy storage and auxiliary heater modes is between 85.07% and 89.1%, respectively[38]. When used to produce hydrogen (H_2), its efficiency increases to 94.15% and 92.05% in the same modes. Which is still less than TG.

In Energy and Human Ambitions on a Finite Planet, Thomas Murphy reasoned that at the historical rate of energy growth since 1650, the Earth will come up against the severe thermodynamic limit of a boiling ocean in 400 years[39]. The only way to prevent this calamitous outcome, while providing the energy modern society needs, is to exclusively use endothermic processes, unlike fission or fusion, that absorb heat from the environment.

7. TG—Anthropogenic heat engines utilizing the global warming resource

The oceans are the only place in the climate system that stores heat. They do this principally at the surface. Between 1971–2018, of the 89% of the heat of warming that went into the ocean, 52% went into the upper 700 m, 28% to a depth of 700–2000 m, and 9% below 2000 m[16]. As **Figure 4** shows, in 2023, the ocean's surface warmed about 8 times more than the temperature increase at a depth of 1000 m.

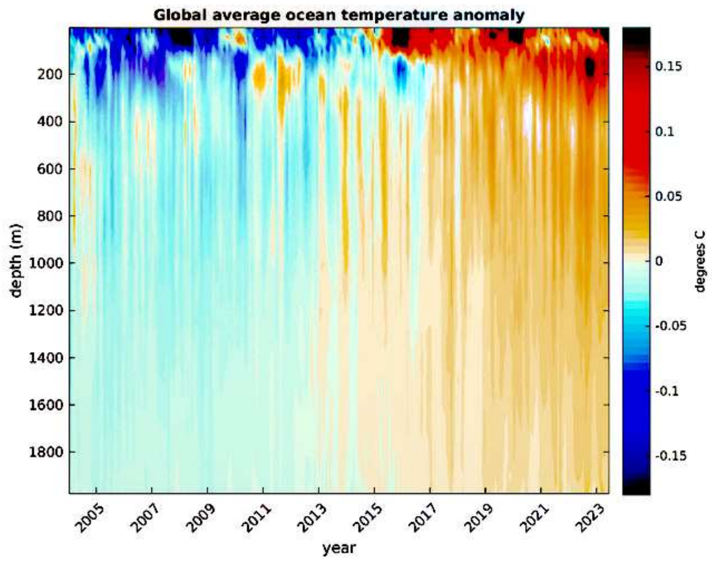

Figure 4. Ocean heat anomaly 2014–2023, 0 to 2000 meters[26].

The closer to the surface, the warmer the water, and since surface heat is problematic, the rational option is to try to relocate the heat of warming as far from the surface as possible, within reason. The thermocline is the layer beneath the ocean's mixed layer where the surface cools rapidly from a temperature of about 13 °C to 4 °C at a depth of 1000 m. After which, the rate of cooling declines very slowly. Therefore, intentionally moving heat below 1000 m is counterproductive. The efficacy of removing heat from the surface is enhanced by the fact that shifting the heat through a heat engine produces energy. And even more so, when this energy can be produced at less than the cost of burning fossil fuels. And even more so when this energy cools the surface and reverses the offgassing of CO_2 from the oceans to the atmosphere. And in fact, with cooling, this offgassing is reversed, and about 4.3 gigatons (Gt) of atmospheric CO_2 moves back into the ocean each year at no cost.

TG is the only productive way the heat of warming can be eliminated from the ocean/atmosphere system. This is an outcome that would be enhanced in an environment where no more emissions are created, and legacy emissions are dissipated to space over the course of about three thousand years.

Warming heat is significantly impacting the climate. But, in the alternative, it could be the catalyst for the fulfillment of the UN's 17 SDGs[29].

Solar energy has the potential to produce 23,000 TW of power and wind 25–70 TW annually, but they are not dispatchable sources of power[20]. They are intermittent, requiring expensive energy storage systems that in turn require metals that are both difficult and ecologically fraught to unearth.

Every square meter of the Earth's surface is impacted by waves, wind, ocean currents, and solar energy, a portion of which can be converted to electrical energy or an energy carrier like H_2 using photocatalytic and photoelectrochemical technologies[40].

The British architect and inventor, Dominic Michaelis, devised the concept of an Energy Island, which is a hybrid approach utilizing each of the above sources to produce energy from the oceans[41]. The design was for a hexagonal platform where wind turbines, solar collectors, wave energy converters, and sea current turbines combine to produce 250 MW of energy from the water and wind flowing beneath and around the island.

Each hexagon has equal sides of 291 m, creating a surface area of 220,000 m^2. The hexagon is segmented into six equilateral triangles. Nineteen percent of the power derived from these hexagons would come from ancillary sources, with the bulk of the energy derived from OTEC per **Table 2**.

Table 2. Various energies derived from a 250 MW Energy Island[41].

Energy Source	Megawatts	% of Total
Wind	18	7%
Wave	6	2%
Sea current	10	4%
Solar	13.5	5%
OTEC	202.25	81%
Total	250	100%

The hexagons are interlockable to facilitate scaling to greater capacities.

The islands are stationary, which is problematic because of the seasonal nature of the OTEC resource. For example, in September, in the Gulf of Mexico, the SST is consistently in the range of 30 °C, which is ideal for OTEC (the ΔT between the surface and 1000 m where the temperature is 4 °C must be at least 20 degrees to produce power)[42]. In March, however, the average temperature of the Gulf is 18 °C, leaving a ΔT of 14 °C which is anergy.

Another problem with the Energy Island concept is that it uses 81% of its ocean real estate to produce only 19% of its power, per **Table 2**. Furthermore, heat released in a condenser within the mixed layer of the ocean is statistically back at the surface within about 3 months; therefore, no climate respite is provided[25]. But even more importantly, at the energy capacity of TG's potential, conventional OTEC cools the tropical surface to the detriment of an equivalent warming of the poles and the fertile fishing grounds off the west coast of South America[43].

TG platforms are designed to be mobile, and capable of seeking out the highest SSTs that become inputs for heat engines that convert the heat to work.

The frontal area is obligatory for harvesting SSTs, but drag is an impediment to forward motion. To reduce drag, TG platforms use a chevron shape to cut through the surface, which in turn provides twice the frontal area along the leading edges of the chevron as the base, which provides rigidity to the equilateral triangle that comprises the upper section of the system.

Whereas the Energy Island produces 250 MW of power using 220,000 m^2 of ocean surface, a 1-GW TG platform would produce the same amount of power using only 42,900 m^2 of ocean real estate.

The frontal area of the chevron is angled top to bottom at 45 degrees to allow for the sloughing off of aquatic life too big to pass through the system's heat exchangers.

Above the submerged evaporators, surface overhangs of 8.5 m, front and back, incorporate wave accumulators and photovoltaic panels, spinnakers used for when the platform is moving downwind on the Trade Winds, and horizontal windmills for going upwind. All of these are incorporated into a 50 m-long surface platform from which 5 MW of ancillary power is produced to provide the impetus necessary to drive the system forward and force water through the system's heat exchangers.

The stripped-down version of an Energy Island embodied by TG provides considerable labor and material savings over the original Energy Island, or any other hybrid OTEC system.

The National Renewable Energy Laboratory estimates the total useful wind farm requires about 250,000 m^2 per megawatt[44]. And the total requirement for 1 megawatt of solar photovoltaics (PV) is 4 acres, or about 16,000 m^2[45]. Whereas, TG's 42,900 m^2 produces 1 GW of power and provides 373 times the solar concentration of PV. This is consistent with the fact that PV is a surface effect, while TG evaporators are thirteen meters deep and boil 6.5 m worth of working fluid to produce the vapor that produces the power in the system's turbine.

PV panel's power productivity, conversion efficiency, and energy cost are affected by environmental factors such as dust, hail, humidity, and temperature and installation element parameters such as inclination angle, installation area, and altitude[46]. None of which are at play beneath the surface. Where the bottom of the evaporator contains 6.5 m of working fluid yet to be boiled.

To produce 1-GW with a TG system, 66 evaporators, 13 m wide by 34 m long by 13 m deep, are required.

The First Generation 50 MW OTEC Plantship design of Michaelis and Vega, incorporated 5–18 MW evaporators with 13 × 34 × 13 m dimensions and an equal number of condensers of the same size in its design[47]. This ship, however, situated its condensers at the surface, which required large cold water pipes to bring cold water from the depths to service the condensers. Whereas the TG design uses heat pipes that are 1/10th the size and are 2.5 times more efficient.

To produce 1-GW with the Michaelis/Vega design, one hundred evaporators and condensers would be required. So, for the TG design, either smaller heater exchangers or fewer of them are required, and the latter design consideration was selected due to a concern about the width of the platforms.

The wider they are, the more difficult they are to maneuver.

The minimum economically viable size for OTEC plants is estimated to be 100 megawatts, and each doubling of this capacity reduces the overall capital cost of larger systems by 22%[48,49].

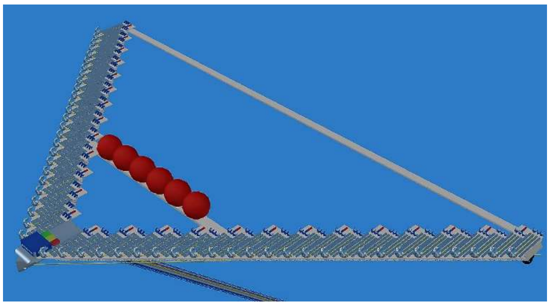

Figure 5. A 1 GW TG hydrogen-production plant.

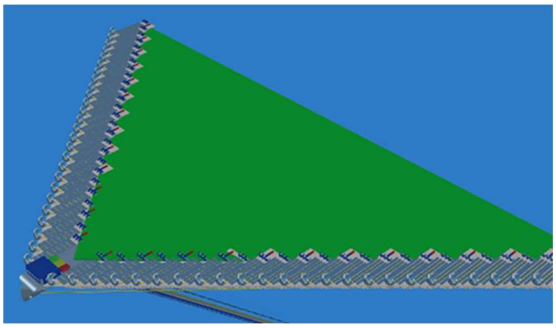

Figure 6. A 1 GW TG electricity production plant with greenfield.

Figures 5 and **6** are conceptual renderings by the author of 1-GW TG plants in an H_2 production configuration, **Figure 5**, and a greenfield format, **Figure 6**, where electricity is produced at sea.

Nobel Laureate Richard Smalley, in his "Terawatt challenge" found that energy was the answer to mankind's next nine concerns, including, water, food, environment, poverty, terrorism and war, disease, education, democracy, and population[50].

The 1-GW chevron would have wings, each side, 429 m long with a 26 m wide hull at the pinnacle of the triangle, making a greenfield of 84,595 m^2, which is 39% of the area of an Energy Island that produces a quarter of the energy.

On TG's green fields, steel, aluminum, cement, and fertilizer plants, which are the hardest industries to decarbonize, could flourish. As could artificial intelligence and data mining operations. Metal and mineral extraction from seawater could be undertaken, amongst a myriad of other opportunities requiring electricity. All in the service of cooling the surface and restoring the environment.

Unlike cryptocurrencies, which some liken to "fool's gold", the oceans contain 47 real minerals and metals, including gold and silver, some of which are already being harvested[51].

TG platforms, harvesting surface heat by passing millions of tonnes of water through their heat exchangers, could be adapted to extract a portion of the 47 quadrillion tons of trace elements that are dissolved in solution (Each liter of seawater contains about 35 g of dissolved salts)[52].

The combined ocean volume is roughly 1.335 sextillion liters of water[53].

Thirty-one thousand 1-GW TG plants, moving 124,000,000 tonnes/sec through their heat exchangers, could move the equivalent of 1.4 quintillion short tons of water (the ocean's total mass) in about 350 years.

Electrical production with TG would be 25% cheaper than H_2 production due to the cost of electrolysers and storage infrastructure. But Green Hydrogen could play a significant role in achieving low and net-zero emissions[54].

Artificial intelligence (AI) technology could contribute to the solution of the energy production problem by using AI for the analysis and prediction of energy production data[55].

Global warming is more energy than can be consumed in a single tranche; therefore, low thermal efficiency makes no difference to the amount of work that can be produced with global warming's copious amount of energy.

An energy carrier like H_2 would be better suited to the conveyance of ocean-derived power to terrestrial consumers than electricity, which can be hazardous in its own right, as evidenced by the California forest fires triggered by the electrical grid[56].

Heat source

The mean date of the Resplandy paper was 2004, and the mean warming was 409 TW[2].

A joint NASA and NOAA study found the Earth's energy imbalance doubled over the 14-year period from 2005 to 2019[57]. This was prior to the International Maritime Organization's introduction of limits on the amount of Sulphur in fuel oil for ships, in 2020[58]. James Hansen et al. estimated an increase in global absorbed solar radiation by 30% over the prior 5-year average[59]. It is assumed therefore it is likely the ocean heat content will be at least 3 times greater than it was in 2004, about 3300 TW, in 2046, which is likely the earliest TG platforms could start reversing the global warming sign.

Although it is beyond the scope of this paper, and since warming has been ongoing for at least 270 years and the TG cycle is 226 years, the 409 TW average of 2004 seems like a reasonable annual objective for reducing the surface heat over the course of 226 years. After which the heat of warming would be depleted by recycling captured ocean heat between the depths of 1000 m and the surface.

8. The climate benefit of anthropogenic heat engines

Richard Smalley's "terawatt challenge" was "To give all 10 billion people on the planet the level of energy prosperity we in the developed world are used to, a couple of kilowatt-hours per person, we would need to generate 60 TW around the planet—the equivalent of 900 million barrels of oil per day"[50]. But this goal runs up against the thermodynamic limit identified by Tom Murphy, whereby the historical growth rate of consumption would demand the total output of the sun used here on Earth in 1000 years[39].

The compromise is endothermic and baseload energy. As **Table 1** demonstrates, TG has three times the capacity of its closest contender and over one order of magnitude more than the rest.

As Smalley ranked them, energy, water, food, and the environment will be the greatest drivers of climate migration[60].

Heat can reasonably be seen as a proxy for the environment and H_2 as a proxy for water. The latter is an energy carrier, unlike electricity, which has a single function, and in a fuel cell H_2 combines with O_2 to produce electrical energy and water, the source of life on the planet, in a process that thermodynamically is the mirror image of electrolysis.

H_2 produced at sea level would have an average hydrological head of 840 m on land, over four times the hydraulic head of the Hoover Dam with a head of 180 m, when combined with O_2 in a fuel cell to produce energy and water[61].

Another proxy for the environment is "sea level rise", especially in conjunction with storm surges, which many see as the greatest risk of warming. Along with saltwater intrusions that destroy fresh groundwater supplies[62].

In the global ocean, the thermal expansion coefficient (TEC) varies from 0.3×10^{-4} °C^{-1} near the freezing temperature (≤0 °C) to 3.5×10^{-4} °C^{-1} in tropical waters[63]. At a depth of 1000 m, it is about half as deep as the tropical surface. Heat moved to a median depth of 500 m with TG heat pipes, which would therefore produce 25% less thermal expansion of the seawater. But more importantly, it would be unavailable to melt ice sheets or glaciers, which currently account for about 21% of the recorded sea level rise of the past two decades[64]. But it could induce 60 m of sea level in the foreseeable future[65].

9. The entropy of carbon dioxide removal from the atmosphere

IPCC AR6 WGIII says, CDR is required to achieve global and national targets of net zero CO_2 and greenhouse gas emissions[66]. One part per million (ppm) equals 2.1 gigatons of carbon (GtC) or 7.8 gigatons of carbon dioxide ($GtCO_2$). But ~55% of emissions are absorbed by oceans or the land, so 1 ppm of emissions or reduction equals 17.3 $GtCO_2$[67]. To go from 11 March 2024, an atmospheric CO_2 concentration of 425 ppm to 280 ppm (the estimated preindustrial level) would require the removal of 2509 $GtCO_2$ plus future emissions[68]. At a removal rate of 40 $GtCO_2$/year net, this would take 63 years. With Negative-CO_2-emissions ocean thermal energy conversion (NEOTEC), 1 gigawatt of electricity production would avoid 1.1×10^6 tonnes of CO_2 emissions/year and consume and store (as dissolved mineral bicarbonate) approximately 5×10^6 tonnes CO_2/year[19].

Thirty-one thousand 1-GW TG plants, as is TG's potential, would therefore sequester 155 Gt of CO_2 in the ocean in one year. The estimated cost per tonne of this sequestration would be $154/tonne so, the total annual cost would be $24 trillion[69]. And the 2509 $GtCO_2$ removal required to return the atmosphere to the preindustrial CO_2 level, would be met in about 16 years. At a total cost of $384 trillion.

And to further complicate matters, the working life of TG plants is about 31 years, so they would sequester about 4900 $GtCO_2$ over their working life at a sequestration cost of about $744 trillion, or equivalent to the global GDP of the next 7.5 years.

Since the atmosphere alone holds about 3276 Gt CO_2 the TG plants would need to start pulling CO_2 out of the ocean.

Beyond the economic incongruity of CDR, its thermodynamics do not add up. The atmosphere holds about 890 GtC compared to 38,000 GtC in the upper, deep, and sedimentary layers of the ocean[70]. If the atmosphere were to become devoid of carbon on account of CDR, entropy would soon ensure that ocean carbon would fill the atmospheric void.

In short, entropy would seek to spread the carbon beyond the oceans.

CarbonBrief estimates that as much as a quarter of global energy will need to be dedicated to CDR by 2100, which has implications for waste heat, as was examined above[71].

The Black Body temperature of the planet is −23 °C, whereas the actual temperature is 15 °C. The difference is the greenhouse gas (GHG) blanket. If 25% of the energy produced by TG was used for CDR, there would soon be no CO_2 in the atmosphere with the result the surface would soon reach the Black Body temperature. Plus, the 2 °C TG removed to the ocean, times 4, for the Stefan-Boltzmann constant, would leave an average surface temperature of −15 °C. Which would make for an equally unhabitable planet as global warming is beginning to make the existing one.

10. The economics of anthropogenic heat engines

TG is a nascent renewable energy technology with a theoretical potential of 31 TW, but this potential is indefinite considering there are no operating commercial plants. And there are knowledge gaps that need addressing.

10.1. Spatial boundaries

OTEC runs on the same fuel as a tropical cyclone. Ocean surface temperatures of 26.5 °C or greater are required to produce a storm. A total of 88 named storms occurred across the globe in 2022, which was near the 1991–2020 average[72]. A single storm can produce as much as 600 TW of energy, at least 20% more than the heat of global warming, so there is no spatial boundary[73]. But for the Small Island Developing States (SIDS), which control 30% of the economic exclusion zones that comprise the prime OTEC areas. But the SIDS doesn't have sufficient electrical demand to justify the cost of OTEC, which demands plants of at least 100 MW capacity to be commercially viable[74].

The other 70% of the ocean are global commons over which no country, technology, or individual will ever hold sway.

10.2. Natural, location-specific influences on the real net power output

In the Atlantic SSTs of 30 °C off the top end of South America and in the Gulf of Mexico are common in September as they are in the Eastern Pacific and Indian Ocean temperatures at that time of year.

March is the peak of the typhoon season in the southern hemisphere, where 30 °C temperatures are still common in the Pacific and Indian Oceans, but south of where those temperatures are reached in September.

In the off-peak storm season between the latitudes 20 degrees north and 20 degrees south latitudes temperatures of 24 °C are common and are at the lower limit for TG energy production.

A ΔT of 6 °C between the surface and 1000 m would make a 24% difference in the output of a TG plant.

10.3. Capital cost

TG systems are an arrangement, in order of cost, of a platform and hull, heat exchangers, turbines, electrolysers (if H_2 is to be produced), pumps, a heat pipe, and an interface between the platform, the pipe, and the condensers and/or the electrolysers situated in deep water.

Large heat exchangers are a function of low thermodynamic efficiency and are linearly scalable in accordance with the requisite power.

Table 3 shows the cost of TG plants based on the literature, where:

1) The 10 MW plant is land based.
2) All other plants have a floating ship design.
3) The cost of the 100 MW plant is 66 percent of the base cost of the conventional 100-MW plant of $4000/kW[75].
4) Each doubling of the size of plants 100 MW or greater lowers plant costs by 22%[76].
5) An inflation adjustment between 2010–2024 of 38% is assumed[77].
6) The cost of ship design using a deepwater condenser is 66% of cold water pipe design[78].
7) The annual operating cost is 5%[79].
8) Energy subsidies for 2023 were $7 trillion USD[80].

Table 3. The historical and projected cost of OTEC and TG.

Plant Size	10	Conventional 100	100	1000
Rating	**MW**	**MW**	**MW**	**MW**
$2010/kw (installed)	$16,400	$4,000	2,640	1,394
Overnight Cost	$164,000,000	$400,000,000	$264,000,000	$1,393,759,224
Number of plants	3,100,000	310,000	310,000	31,000
Total Cost OTEC	$508,400,000,000,000	$124,000,000,000,000	$81,840,000,000,000	$43,206,535,944,000
Inflation Adjustment (38%)	$701,592,000,000,000	$171,120,000,000,000	$112,939,200,000,000	$59,625,019,602,720
Interest at 5.5% for 30 years	$701,592,000,000,000	$171,120,000,000,000	$112,939,200,000,000	$59,625,019,602,720
Principal plus interest	$1,403,184,000,000,000	$342,240,000,000,000	$225,878,400,000,000	$119,250,039,205,440
Plant life in years	30	30	30	30
Capacity	95%	95%	95%	97%
Annual operating cost	5%	5%	5%	5%
Annual cost per year	$25,848,126,315,790	$6,304,421,052,632	$4,160,917,894,737	$2,151,418,233,088
Terawatt hours	271,560	271,5560	271.560	271,560
Kilowatt hours	271,560,000,000,000	271,560,000,000,000	271,560,000,000,000	271,560,000,000,000
Cost per hour	$0.095	$.023	$.015	$0.008
Annual fossil fuel subsidy	$7,000,000,000,000	$7,000,000,000,000	$7,000,000,000,000	$7,000,000,000,000
Annual (loss) return	$18,848,126,315,790	$695,578,947,368	$2,839,082,105,263	$4,848,581,766,912

In 2022, global energy costs were 13% of a global GDP of $101 trillion[81,82]. This is 6.5 times the cost of TG, not including the IMF's estimated $7 trillion for the environmental cost of doing business burning fossil fuels.

Oil prices have reached their highest level since 2008, and higher energy prices in general have contributed to sharply increased inflation, which has led to widespread political unrest[83].

A recent study of OTEC for Indonesia shows 45 GW of OTEC capacity can be installed for a Net Present Value (NPV) of up to $23 billion (this is for conventional OTEC, which is 33% more expensive than TG), so **Table 3** is in the ballpark[84].

10.4. Operational cost and useful lifetime

The operational life of an OTEC system is estimated to be 30 years[74]. And the annual operating cost is estimated to be 5% of the capital cost[79].

10.5. The impact of interest rates

Table 3 calculates interest at 5.5% over 30 years, which equals the capital cost. The Stern Review on the Economic Effects of Climate Change, however, argued that any discounting is ethically inappropriate for a global issue like climate change. However, a minuscule discount rate of 0.1 percent per annum might be justifiable[85]. Over the 30-year life of the plants, this would total 3% of the capital cost and reduce the total cost of 31,000 plants by about $57 trillion.

10.6. Speed, can the technology be deployed in time to make a difference in the climate

Universities are failing to meet the growing demand for a clean energy workforce. Since a career may last 30–40 years, this creates a risk of long-term carbon lock-in and stranded skill sets through (mis)education[86]. Even if this wasn't the case, it will take at least 10 years of R&D and scaling from a 300-watt, closed system, that confirms the thermodynamics, confirms the movement of atmospheric CO_2 to the ocean as the surface cools, and tests various working fluids, to 10 MW, 100 MW, and 1-GW ocean going plants. After the 1-GW scale is attained, it will take another 10 years to ramp up to 1000 plants a year.

In 2022, there were 105,395 registered vessels[87]. Current worldwide shipyard capacity is about 1200–1300 ships per year, compared with about 2000 ships per year between 2005 and 2010[88]. Seventy-five percent of these plants were built by only three countries: China, Korea, and Japan[77]. Should global warming finally, widely, be recognized as the existential threat it is, the other 192 countries of the world are likely to make a commensurate effort to solve the problem. Which would entail the production of at least 1000 1-GW ships a year.

Since the working life of these plants is 31 years, and the objective is to produce 31 TW of energy, the oldest ships would be replaced each year to maintain a stable energy supply.

10.7. Does the technology scale

According to Langer and others, it does[74,84].

10.8. Availability of resources

If there were enough resources to build 2000 ships per year between 2005 and 2010, it is reasonable to assume there are enough resources to build 1000 TG plants a year[77].

Magnesium, currently valued at about $2600/tonne, exists at a concentration of 1272 ppm in seawater, 3 times higher than the concentration of CO_2 in the atmosphere.

It is a viable metal for use in many major components, mainly heat exchangers and heat pipes in TG plants[89].

A method of precipitating magnesium from seawater has been known for over a century and new techniques have been discovered more recently[90,91].

Magnesium alloys reduce the weight of heat-removing elements like TG heat exchangers by a third without losing efficiency[92]. With the ocean's abundance of magnesium and the technical ability to secure it, the current cost of the metal would be reduced by orders of magnitude when the metal is produced as an adjunct to energy production using the TG method.

10.9. Equity

The SIDS are the most vulnerable nations to the global warming risks of sea level rise, storm surge, and the vagaries of fossil fuel costs. But paradoxically, they control 30% of the EEZs in the most promising OTEC regions.

They could leverage these EEZs in return for free energy, among other considerations, and offer their territories as test beds for the nascent TG technology, benefiting mankind even if only inadvertently.

10.10. Fairness

The concept of a "just transition" away from fossil fuels is a concept that says to meet our climate goals, all communities, all workers, and all social groups must be brought along in the pivot to a net-zero future[93]. It is a concept designed to include and therefore bring on board as many interested parties as possible.

Workers in the fossil fuel industry would be the most impacted by a phaseout of their resource, but they also have the most experience and technology working in deepwater, so they need never suffer for a lack of jobs during and after a "just transition."

Minimizing the existing occupational health and safety risks of people working in all institutions is the main task of any occupational health and safety culture and is another milestone that TG would meet[94].

10.11. Economic analysis

Since there is no operational experience with large OTEC or TG systems, the best alternative is to take the example of a Nimitz-class aircraft carrier, which is indestructible by the elements when under power and commanded by a competent captain.

TG plants will operate exclusively within the Inter-Tropical Convergence Zone (ITCZ), in which cyclones, hurricanes, and typhoons do not occur, but where vigorous thunderstorms are interspersed with the doldrums, which are periods of calm that have stranded sailors for days or weeks.

The predicted service life of Nimitz-class aircraft carriers is about 50 years, but it is assumed that the service life of an OTEC platform is 31 years [74]. In 1997 dollars, the CapEx for the carrier was $4.1 billion, and its maintenance costs were $5.7 billion[95]. This is in line with an overnight cost of $1.4 billion for a 1-GW TG plant plus a 150% maintenance cost over 30 years.

11. Conclusion

The thermodynamics of global warming invite the conclusion that the more energy produced by the heat of warming, the cooler the surface becomes, sustainability goals are met, and the impacts of global warming are mitigated. TG redistributes the certain accumulation of ocean heat and removes a part of it to the land in the service of as many as ten billion people. This is heat that is currently lying fallow and, in the alternative, will ultimately resurface and wreak havoc. Its use can cool the surface, and when deployed at scale, it could generate 1.6 times the world's current primary energy while removing CO_2 from the atmosphere and solving the fossil fuel replacement problem. The infrastructure is capital intensive, but this is capital that is in many cases also lying fallow and instead could be generating prodigious economic returns and climate respite[96]. To derisk this capital, a lab-scale, and small ocean-going prototype should be financed and constructed as soon as possible.

Conflict of interest

The author declares no conflict of interest.

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