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Review

A 7th Law of Thermodynamics and its climate implications

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Abstract: Conversion of the ocean's vertical thermal energy gradient to electricity via OTEC has been demonstrated at small scales over the past century. It represents one of the planet's most significant (and growing) potential energy sources. As described here, all living organisms need to derive energy from their environment, which heretofore has been given scant serious consideration. A 7th Law of Thermodynamics would complete the suite of thermodynamic laws, unifying them into a universal solution for climate change. 90% of the warming heat going into the oceans is a reasonably recoverable reserve accessible with existing technology and existing economic circumstances. The stratified heat of the ocean's tropical surface invites work production in accordance with the second law of thermodynamics with minimal environmental disruption. TG is the OTEC improvement that allows for producing two and a half times more energy. It is an endothermic energy reserve that obtains energy from the environment, thereby negating the production of waste heat. This likewise reduces the cost of energy and everything that relies on its consumption. The oceans have a wealth of dissolved minerals and metals that can be sourced for a renewable energy transition and for energy carriers that can deliver ocean-derived power to the land. At scale, 31,000 one-gigawatt (1-GW) TG plants are estimated to displace about 0.9 W/m^2 of average global surface heat into deep water, from where, at a depth of 1000 m, unconverted heat diffuses back to the surface and is available for recycling.

Keywords: marine energy; global warming; heat to work; heat engine; waste heat; ocean thermal stratification; global energy supply

1. Introduction

In 1922, Alfred J. Lotka, building on principles from statistical physics and the second law of thermodynamics, particularly the work of Ludwig Boltzmann, articulated the MPP that living organisms need "available energy" from their environment to survive and thrive and that organisms that best harvest energy from their environment will be more successful, leading to larger populations and greater biomass. In his 1950 Ph.D. dissertation, H. T. Odum proposed, based on Lotka's work and Charles Darwin's theory of natural selection, a 4th Law of Thermodynamics that proposes maximization of power for valuable purposes is the criterion for natural selection [1]. In his 1996 book "Environmental Accounting: Emergy and Environmental Decision Making," Odum proposed a 5th law suggesting energy flows through the universe are organized in a self-organizing hierarchy for maximum empowerment [2]. And in 2001, Odum proposed the coupling of biogeochemical cycles to energy transformation hierarchies in a 6th law that proposes energy must be degraded to concentrate materials and that the quantity of material flow also decreases in each successive step in a series of energy transformations [1].

The purpose of this paper is to propose a 7th Law of Thermodynamics that is an amalgam of the MPP and the law of supply and demand, which states that if a product, including energy, that is a product of an exothermic reaction thereby releases heat into the environment is in high demand and low supply, the price will increase. Conversely, if there is low demand, as is the case of an endothermic reaction that imports energy from its surrounding environment, the energy is a reactant and is in plentiful supply, and the price of the energy will decrease.

Energy is vital to living organisms, but an economic imperative drives a large swath of humanity. The lower the energy cost, the more society can consume and the more successful it will be as a species. The most plentiful and cheapest available energy source is impeded by its perceived high capital cost. A 7th Law of Thermodynamics incorporating the MPP and the Law of Supply and Demand can break this embargo and complete the suite of thermodynamic laws, making them a unifying law of energy and economics plus a blueprint for a holistic solution to one of the century's most significant challenges.

2. Energy sources

Reasonably recoverable reserves are the quantity of a resource reliably determined to exist and that can be recovered under current technological and economic conditions [3]. To be reasonably assured, there must be a high level of confidence in the existence and recoverability of the resource based on geological evidence and engineering data, which is often obtained through drilling and sampling of an area. Furthermore, to be recoverable, there must be enough of the resource that it can be extracted with existing technology and under current economic conditions in view of the cost of extraction, market prices, and regulatory or environmental constraints.

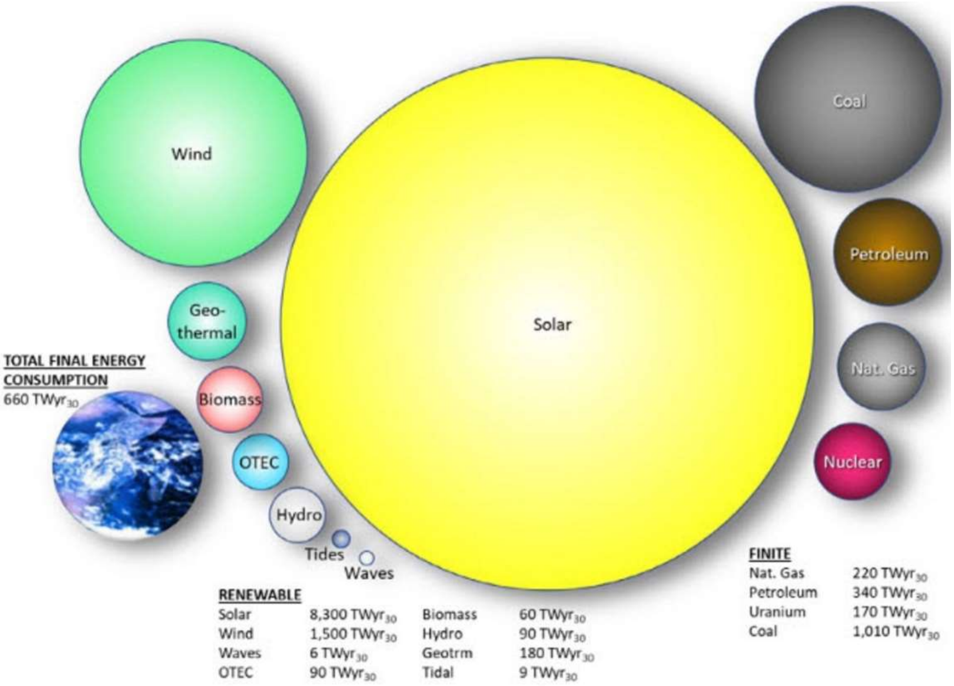


Figure 1. Estimated finite and renewable planetary energy reserves.

Annual yield is shown for the renewable resources. Total recoverable reserves are shown for the finite resources. Yearly potential is shown for the renewables (the volume of each sphere is proportional to the corresponding reserve).

Per **Figure 1**, Perez and Perez, for renewable resources, extended the definition of 'reasonably recoverable reserves' to a 30-year lifecycle to be consistent with the long-term reserve numbers for conventional finite resources (the 30 years commonly used for economic assessments and planning purposes). All reserves in **Figure 1** graphic are reported in TWyr and given the 30-year time frame considered for renewables and consumption, as $TWyr_{30}$ [4].

3. Global warming as an energy problem

EEI is a fundamental measure of climate change that encompasses changes in climate patterns, including global warming, but also changes in precipitation, extreme weather events, and impacts on natural and human systems [5]. Global warming is the persistent rise in Earth's average surface temperature due to human activities that increase greenhouse gas concentrations in the atmosphere, leading to environmental and societal impacts, including heatwaves, melting ice, rising sea levels, and disrupted ecosystems. EEI is the difference between the amount of solar energy absorbed by the Earth and the amount of energy the Earth radiates back into space. It is estimated to be 0.9 W/m^2 of the Earth's total surface of $5.1 \times 10^{14}\ m^{-2}$ or about 460 TWyr or 13,800 $TWyr_{30}$ [6], which is 115% more than the total of all the energy sources shown in **Figure 1**. Moreover, the rate of the EEI is rising. Satellite data from the Clouds and the Earth's Radiant Energy System have shown that the EEI doubled between 2005 and 2019 [7]. Ocean heat content data shows about 90% of the EEI has been absorbed by the ocean, and the World Meteorological Organization has reported that the upper 2000 m of the ocean continues to warm at a significant rate [8]. Per **Figure 2**.

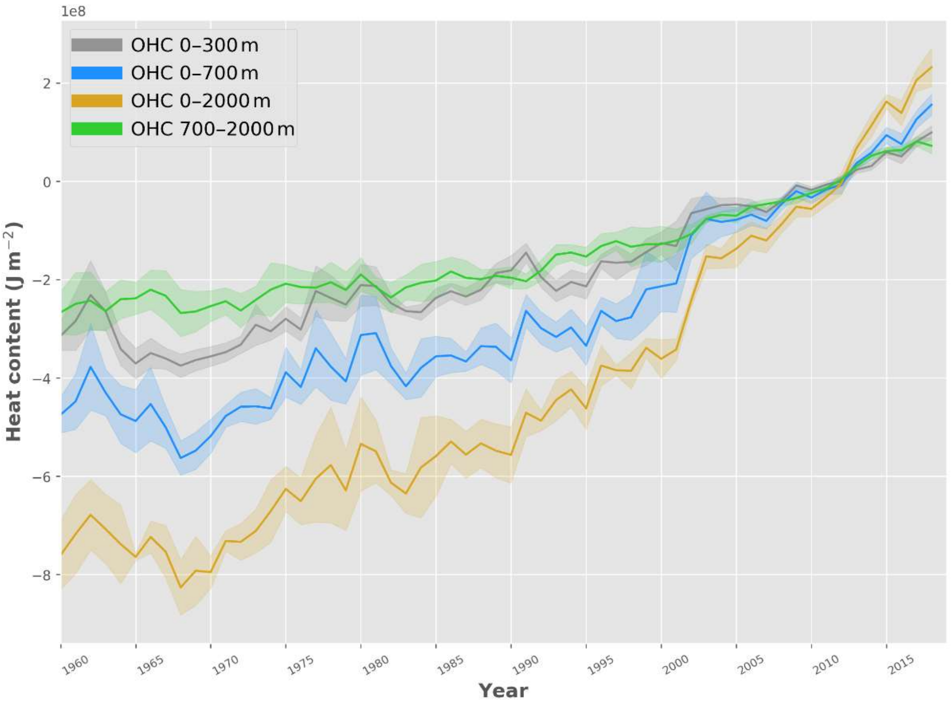


Figure 2. Ensemble mean time series and ensemble standard deviation (2σ, shaded) of global ocean heat content anomalies relative to the 2005–2017 climatology for the 0–300 m (gray), 0–700 m (blue), 0–2000 m (yellow) and 700–2000 m depth layer (green) [9].

Global warming is an outcome of energy use. The burning of fossil fuels is the primary source of GHG emissions, particularly CO_2, that trap heat in the atmosphere. Natural gas, primarily composed of methane, is a potent GHG that leaks during its extraction and transportation and is another major contributor to global warming. As are other gases like nitrous oxide released by the burning of fossil fuels and fluorinated gases from industrial processes. Rising global energy demand driven by population growth, industrialization, and economic development exacerbates global warming, as does the waste heat of energy consumption and inefficient energy usage [10]. Transitioning to renewable energy is vital to mitigating global warming. However, solar and wind are intermittent, and the other baseload renewable energy sources listed in **Figure 1** total only about 66% of current energy consumption. With the proviso, the 90 $TWyr_{30}$ for OTEC shown in **Figure 1** is a gross underestimation of the technology's potential, as is discussed below. Furthermore, fusion energy, touted by some as energy's Holy Grail and not shown in **Figure 1**, is advanced as a proxy for all exothermic energy sources [11].

The UNFCCC secretariat is the United Nations entity tasked with supporting the global response to the threat of climate change [12]. Its 1992 objective was to stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous human interference with the climate system in a time frame that allows ecosystems to adapt naturally and enables sustainable development [13]. If the use of fossil fuels had ceased in 1992, a safe Holocene climate could have been maintained. However, fossil fuel usage has increased because atmospheric CO_2 levels are now 40% higher than human civilization has ever witnessed, increasing by 0.6% annually (2.57/421 ppm) [14].

There is significant inertia to a voluntary reduction of fossil fuel consumption despite the environmental and climate imperatives to do so [15]. Many economies are heavily dependent on fossil fuels, and shifting away from that energy source will require significant changes in infrastructure and technology, which can be costly and disruptive. Fossil fuels have been relatively cheap and abundant, providing a stable and reliable energy source, and the alternatives will require substantial upfront investments and technological development to become cost-competitive. The fossil fuel industry provides jobs and supports various sectors such as mining, transportation, refining, and petrochemicals, so transitioning away from fossil fuels will lead to job losses and economic downturns in regions reliant on these industries. Significant capital investments in existing fossil fuel infrastructure could be lost if those assets are abandoned before the end of their useful lives and the industry wields considerable political power and influence that can impede the policy changes necessary for transitioning to cleaner energy sources. Many countries prioritize energy security, ensuring they have a stable and independent energy supply, which fossil fuels have historically provided. Global markets are deeply intertwined with fossil fuels, and a shift away from fossil fuels could destabilize them, leading to economic uncertainty and fluctuations. While renewable energy technologies have advanced, they still face challenges in terms of efficiency, storage, and scalability; therefore, fossil fuels will, at best, and for decades, continue to be a bridge to a renewable energy future [16].

Fossil fuel drawbacks, such as GHGs, lead to significant global warming and climate change impacts, including more frequent and severe weather events, increased sea-level rise, and disruptions to ecosystems and agriculture. Extracting, transporting, and burning fossil fuels can cause significant environmental damage, including oil spills, habitat destruction, air and water pollution, and soil contamination. These activities harm biodiversity and degrade natural ecosystems. Fossil fuel burning releases pollutants like sulfur dioxide and nitrogen oxides that can cause respiratory and cardiovascular diseases, cancer, and premature deaths, which can be avoided with the improved air quality and public health that renewable energy can deliver [17]. Renewable energy sources are local and inexhaustible, enhancing energy security while reducing vulnerability to geopolitical conflicts and market fluctuations that fossil fuels have historically produced [18]. Transitioning to renewable energy can drive economic growth by creating new industries and job opportunities that can lead to more resilient and diversified economies [19]. Although there are upfront costs associated with transitioning to renewable energy, the enduring savings can be substantial. Renewable energy sources have lower operating and maintenance costs compared to fossil fuel infrastructure, and the cost of renewable energy technologies has been steadily decreasing. Fossil fuels are non-renewable resources, and their extraction becomes more difficult and expensive over time as reserves are depleted; therefore, transitioning to renewable energy affords a more sustainable and long-term energy future.

Addressing climate change and environmental degradation is a moral imperative for ensuring a livable planet [20]. Nevertheless, governments and businesses focus on short-term economic growth and profits, whereas the benefits of transitioning to renewables are more persistent. As the following demonstrates, both short- and long-standing economic growth, profits, and “available energy”, as well as resources that all living organisms need to survive and thrive in their environment, are available in the oceans and are the wages of ocean thermal energy conversion.

4. OTEC as a sustainable source of energy for mankind

Perez and Perez qualified their estimate of 90 $TWyr_{30}$ (3 TWyr) for OTEC in **Figure 1**, cautioning, “OTEC’s economic potential is unknown as it is still an immature technology with no commercial plant operating” [4]. And the UN’s GESAMP has sanctioned this position by pointing out, “After more than four decades of research and development, OTEC has still not been deployed at scale” [21].

In 1998, a team led by physicist Martin Hoffert from New York University determined that stabilizing the Earth’s atmospheric CO_2 levels would require a tenfold increase in carbon-emission-free power generation over the following 50 years [22]. At that time, only 1.5 TWyr of carbon-emission-free power was being produced. So, to achieve the stabilization the team was seeking, Hoffert’s team concluded that non-fossil-fuel energy sources would need to deliver at least 50% of the projected 30 TWyr global power demand by 2050. Therefore, carbon-emission-free power generation will need to reach 15 TWyr by the middle of the century.

Seven years later, Richard Smalley offered his 60 TWyr challenge, which noted in a list of the top 10 issues facing humankind, at the top of which was energy, that it was also the solution to the remaining nine concerns [23].

In 2005, it was determined the worldwide power resource that could be extracted from the steady-state operation of OTEC was estimated at 3 TWyr [24]. Since this was only a fifth of the energy Hoffert's team was seeking, OTEC was and subsequently has remained, until recently relegated to the list of potential renewable energy also-rans.

At this formative stage of the carbon divestment and renewable investment era, OTEC was handicapped by a lowballed potential that its proponents have never recovered from.

Subsequently, OTEC's maximum annual net power production has been reassessed upward to at least 31 TW [25]. And it is the contention of this paper that for the next 3000 years, TG can deliver 31 TWyr of energy by converting the heat of global warming to work, which in turn mitigates every consequence of global warming while returning atmospheric CO_2 levels to their preindustrial level, and it can produce 25 TWyr in perpetuity thereafter (Jia et al. estimated the lower steady-state OTEC power maxima was 8 to 10.2 TWyr, but TG has 2.5 times the efficiency of conventional OTEC, thus as much as 25 TWyr can be supplied in perpetuity) [26].

In 2018, the Jia et al. paper also rebutted the 2015 paper of Kwiatkoski et al. that used a model that boosted the background diffusivity of the top 1000 m of the ocean by a factor of 600 and then regarded this as a proxy for the large-scale effects of technologies like OTEC that rely on seawater properties from different vertical layers [27]. To this day, the GESAMP continues relying on the Kwiatkoski paper by claiming "that large-scale deployment of OTEC heat pipes for purposes of thermodynamic geoengineering would be potentially disruptive to the marine environment considering that, by definition, it would significantly reduce sea surface temperatures on a regional scale while having all the same localized environmental outcomes as conventional OTEC [21].

The paper "Addressing the Urgent Need for Direct Climate Cooling: Rationale and Options", on the other hand, argues that direct climate cooling approaches, like OTEC, have the potential to reduce local to global portions of human-induced warming [28]. What's more, of the 14 cooling methods listed in this paper, only two, MEER and OTEC, generate the energy species need to survive, while the other thirteen radiate energy away from the surface. In the case of MEER, reflection is the technology's primary function and is degraded when its mirrors are focused on a point source for the purpose of producing energy from a concentrated solar system. Whereas solar energy is intermittent, OTEC is baseload [29].

The technical and economic feasibility, long-term impact and efficiency, environmental impact, potential risks, and ethical considerations associated with large-scale ocean-based energy conversions are beyond the scope of this paper but are addressed in the papers "Global Warming, a Global Energy Resource, Negative-CO_2-Emissions Ocean Thermal Energy Conversion, and the book Thermodynamic Geoengineering: The solution to global warming!" [25,29,30]. In summary, these documents reveal that no showstoppers impede the testing of this technology. At least in the eyes of the most populous nations, the ones at most risk of the impacts of climate change, the energy price takers, those bereft of their own natural resources, or internal energy sources. Should any problems arise during the scaling of this solution, the research of Rajagopalan and Nihous in the paper "An Assessment of Global Ocean Thermal Energy Conversion Resources with a High-Resolution Ocean General

Circulation Model" indicate, "When turning off the prescribed OTEC sources and sinks in the model, the environment is shown to relax to its pre-OTEC condition. The time scales for both reverse and direct processes are similar" [31]. At a scale of 100 MW or greater, TG becomes economically viable and profitable, allowing for the plowing of profits into R&D scaling and the buildout of the fleet of platforms necessary to reverse surface heating and global warming.

Three thousand years is 100 times the 30-year economic assessments and planning period shown in **Figure 1** for "finite" energy sources. Times 31 would be 93,000 TW, or 53 times the finite sources shown in **Figure 1**. Over the course of these 3000 years utilizing TG technology, the EEI would be depleted to zero. With TG, surface temperatures would be returned to the preindustrial level in 226 years, at about the same rate of decline as it increased, and would be maintained by recycling the heat trapped in the ocean 12 more times [25].

The approximate linear rate of global warming between 1970 and 2008 was around 0.18 ℃ per decade, based on analyses of global temperature data [32]. However, in recent years, the rise in global surface temperatures has exceeded this long-term trend, with eight of the past nine years recording higher temperatures than the historical average. In 2023, former NASA scientist Dr. James Hansen and his colleagues published a paper titled "Global Warming in the Pipeline", which argues that the rate of warming is expected to increase to between 0.27 ℃ and 0.36 ℃ per decade over the next 30 years, which represents a 50% to 100% increase in the rate of warming since 1970 [33].

The heat of global warming is potential energy that can be converted to work at an efficiency of 7.6%, with the remainder being transferred to 1000 m from where it returns to the surface in about 226 years [34]. The diffusion rate of heat from deep water is one cm/d below the mixed layer (four meters a year) and one meter/d through that layer; therefore, the 226-year period. After which 92.4% of the initial heat can be recycled [35]. Through repeated recycling, virtually all the warming heat can be converted to work, and the waste heat of those conversions can be dissipated to space, effectively managing the excess heat while mitigating rising global temperatures.

The 7.6% efficiency rate of conversion of surface heat to work was calculated by Los Alamos Labs experimental physicist Melvin Prueitt in his 2007 patent filing, "Heat transfer for ocean thermal energy conversion" [34].

Global warming generates more energy than can be consumed in a single tranche; therefore, the low, in engineering terms, thermal efficiency of converting warming heat to work does not limit the amount of work that can be produced from the heat of global warming. Converting the heat of warming heat, which is a surface effect, to work and to sequester the balance mitigates every consequence of global warming, including the decline of Arctic Sea ice, melting glaciers, decreasing snow cover, rising sea levels, the frequency and strength of storms, increasing humidity, and the rising heat content of the oceans [31,36]. The conversion of ocean heat to work that is undertaken on land is an extraction of heat from the ocean.

The fundamental measure of global warming is the heat uptake of the ocean, which is incontrovertible evidence that the Earth is warming [37].

Resplandy et al. used the measurement of atmospheric O_2 and CO_2 levels as the oceans warm and release these gases as a proxy for global warming. They calculated that between 1991 and 2016, the average warming amounted to about 1.29 ± 0.79 × 10^{22} joules of heat (409 TW/year), equivalent to a planetary energy imbalance of 0.80 ± 0.49 W/m^2 of the Earth's surface [38]. They determined that about 1.11 ± 0.68 per meg (parts per million (ppm)) of these gases were going into the atmosphere on account of the warming of the tropical surface annually, with the concentrations of these gases being 1 part O_2 to 1.05 parts CO_2. So, about 0.56 ppm of CO_2 was added to the atmosphere each year of the study.

The mean date for the Resplandy paper was 2004, and the mean rate of warming was 409 TW, so it can be assumed there will be about three more doublings of this amount of heat to at least 3300 TWyr by 2053, the earliest we are likely to be able to start bringing temperatures under control by doubling the current installed capacity of 100 kW/yr of OTEC power every year. Since it is assumed that it will take 226 more years to bring the surface temperature down to the preindustrial level, the conversion of about 409 TWyr to work each year going forward from 2053 would accomplish that goal.

Figure 3 is a depiction of a perceived route to scaling TG plants.

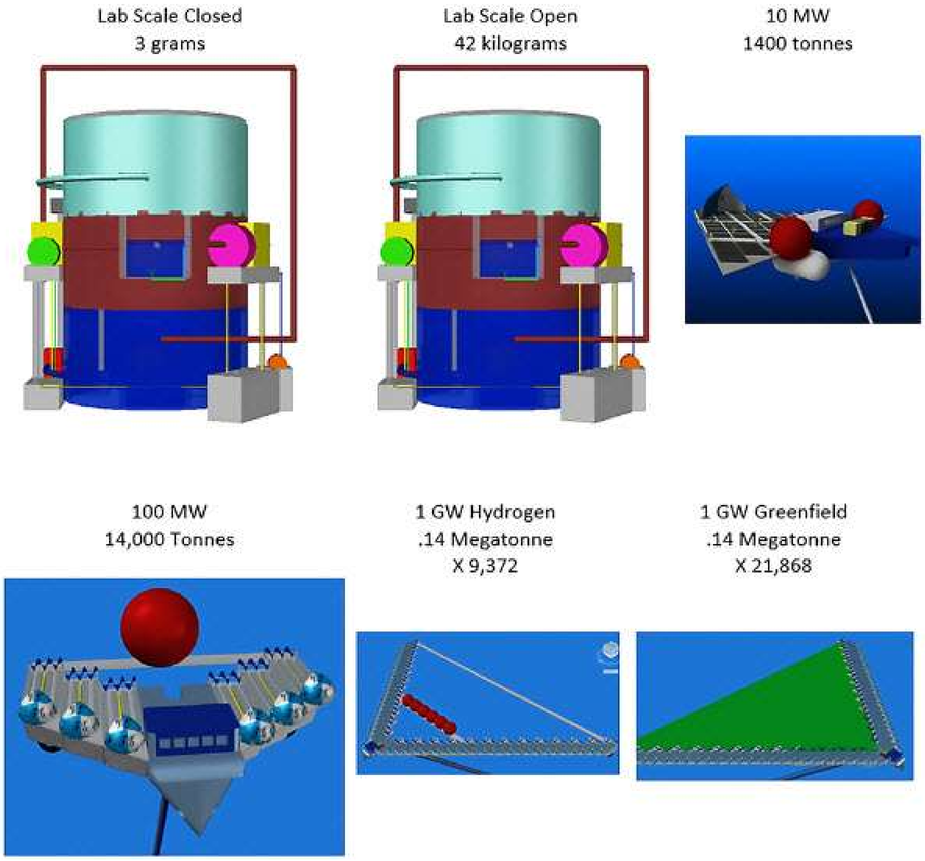


Figure 3. A depiction of a perceived route to scaling TG plants from a closed lab scale model to 1 GW capacity and beyond. The lab scale model was one of the qualified entries in the $100M XPRIZE for carbon removal and the figure shows the quantities of CO_2 that would be sequestered by the various-sized systems and the number of plants that would be required to produce 31 TWyr of power.

5. The ocean thermal dam

Between 1844 and 1854, the English scientist J. P. Joule worked on the problem of the relation between the amount of work spent to bring about the liberation of heat and the amount of heat that was liberated by that work [39]. He used a paddlewheel device submerged in a heat-insulated vessel attached by a series of pulleys to a weight. As the weight fell, it imparted rotation to the paddle that, in turn, produced heat inside the vessel. The work done was determined to be equal to the decrease in the potential energy of the weight (gravity times the distance the weight fell). Through multiple experiments, Joule discovered the direct proportionality relationship between spent work and the quantity of heat obtained (his mechanical equivalent to heat) is 0.002345 kcal/kgf-m. A "Joule," therefore, equals 427 kgf·m/kcal, which is the equivalent of 4.19 watts. It is equivalent to a 1-kilogram mass (m) of water raised to a height (h) of 427 m times gravity (g) (equal to 9.8 m/s²), producing a PE equal to m × g × h, as expressed in the International System of Units joules per kilogram.

A ΔT of 26 °C between a tropical surface and water at a depth of 1000 is equivalent to a PE of 11,102 m times the Carnot efficiency, which is 7.6% for TG × 0.5 (because this potential is considered to be reversible) = 421 m. Or just under twice the height of the Hoover Dam. Moreover, this untapped PE can be found throughout the tropics, where the average surface temperature ranges between 25 °C and 28 °C, and at a depth of 1000 m, it is 4 °C, so the average Δ ranges between 21 °C and 24 °C.

6. The physics

The law of conservation of energy dictates that energy can be transformed from one form to another but can be neither created nor destroyed.

The second law of thermodynamics governs heat engines that conduct heat from hot regions to cold to produce work. Since they cannot do this thoroughly, some of the input heat is dissipated into the environment.

The first law of heat engines is expressed as: $W = Q_H - Q_L$

where:

W is the work output by the engine expressed in Joules (J);

Q_H is heat input from a hot reservoir expressed in Joules (J);

Q_L is heat released into the cold reservoir expressed in Joules (J).

Figure 4 is a schematic representation of the first and second laws of thermodynamics.

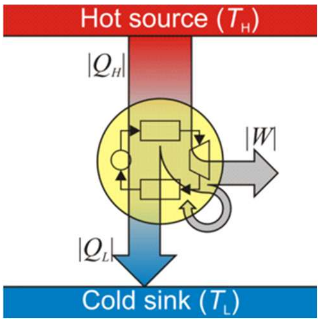


Figure 4. A schematic representation of the first and second laws of thermodynamics.

Heat (Q_H) from a hot source like the tropical ocean surface, moved through a heat engine (in yellow) consisting of an evaporator, a turbine, a condenser, and a pump, produces work (W) and waste heat (Q_L) that is released as the latent heat of condensation of the working fluid from the condenser to the cold ocean at a depth of 1000 m. Some of the work is circulated back into the system to power the pump required to force the condensed working fluid back into the evaporator.

The thermal efficiency of a heat engine is defined as the ratio of the work output to the heat input, expressed by the formula: $W = Q_H - Q_L/Q_H$

The French engineer, Sadi Carnot, showed that the ratio of Q_H to Q_L is the same as the ratio between the high temperature (T_H) and the lower temperature (T_L) of a heat engine. Therefore, Carnot efficiency is expressed as: $1 - (T_H - T_L)/T_H$.

Since the Carnot cycle is an ideal, the Rankine cycle represents the actual processes of a power plant using a vaporized working fluid and is less efficient than the Carnot cycle because it includes entropy and heat losses.

For the prime energy-producing OTEC region of the ocean shown in **Figure 5**, the theoretical Carnot efficiency is assumed to be about $1 - ((301 - 277)/301)$ or 8%.

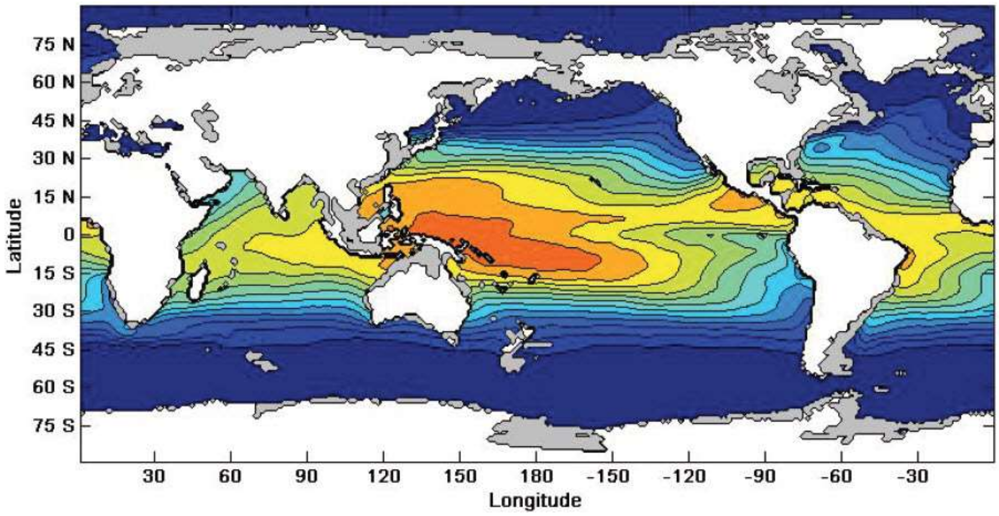


Figure 5. A schematic of the prime OTEC-producing regions.

Shaded from red to yellow, where red represents the region of the ocean where the surface temperature is at least 28 °C, and each gradation down to yellow represents a 2 °C decrease in surface temperature [40]. The blue regions have surface temperatures of 18 °C or less, which is anergy, meaning they are incapable of producing work.

Conventional OTEC uses a CWP in blue to bring cold water to service a condenser near the surface per **Figure 6**.

A CWP plant transfers heat irreversibly and supplies entropy at various points in the cycle. As modeled by Nihous, the thermal efficiency of such a cycle is typically half the turbogenerator efficiency of about 85% times the Carnot efficiency, or about 3.4% [41]. The Carnot efficiency is halved because Nihous introduced the concept of a heat ladder, where about a quarter of the surface heat is lost to the evaporator and its pinch point, another quarter is lost to the condenser and its pinch point, and only about half of the heat is converted to work in the turbogenerator.

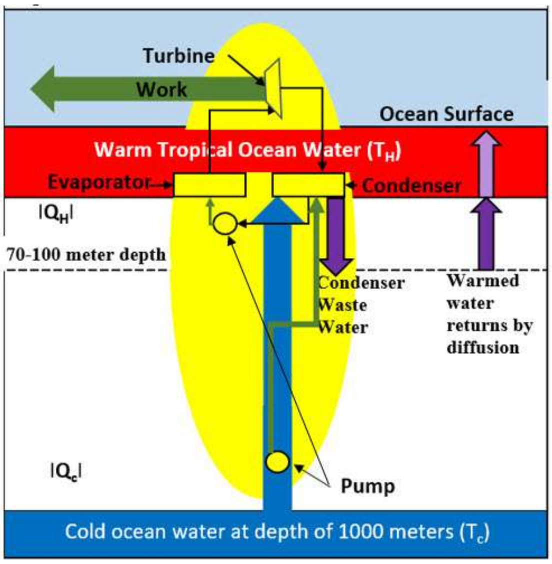


Figure 6. A schematic (not to scale) of conventional OTEC.

Figure 7 shows the functioning of TG, which uses a heat pipe, also referred to as a deep-water condenser or a heat channel, which is the most effective passive method of transferring heat available today [34].

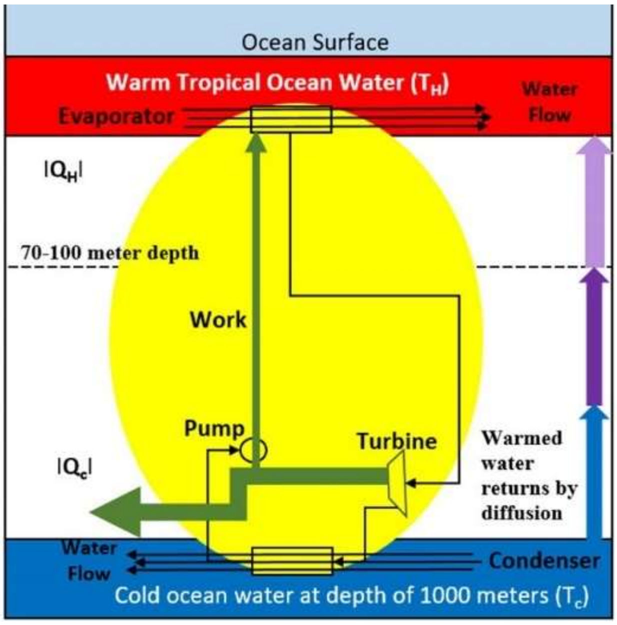


Figure 7. A schematic (not to scale) of the thermodynamics of TG and in yellow is the configuration of its heat engine.

Water passes through an evaporator at the tropical ocean surface to boil a working fluid to supply a vapor that drives a turbine, either at the surface or in deep water, to produce work. A condenser, which is contiguous to the cold-water source at a depth of 1000 m, converts the spent working fluid vapor from the turbine back to a fluid that is then pumped up to the evaporator to complete the work cycle. Wastewater from the condenser returns to the surface by diffusion, where it can be recycled. The work produced by the turbine and the losses incurred by the pumps are indicated in green.

An obvious departure from the design shown in **Figure 6** is the fact that the warm water remains on the ocean surface and the cold water remains in the deep.

With Nihous' heat ladder, half of the heat of the CWP design is lost to the condenser and the evaporator, which for an OTEC ΔT of 24 would be a loss of 12 ℃. But Melvin Prueitt concluded that with a heat channel (heat pipe), the heat losses through the evaporator and condenser would be limited to 4 ℃, 2 ℃ respectively [34]. Due to the fact that hot surface water is contiguous to the evaporator and cold water is contiguous to the condenser, both can be used to boil the working fluid and to condense the vapor that has passed through the turbine. He also determined that a vertical column of ammonia vapor 1000 m long would warm by 5.3 ℃ as it was compressed by the weight of the vapor above it, increasing its temperature and pressure. As a result, the system efficiency of his design was calculated to be 7.6%, or about 2.5 times the efficiency of conventional OTEC. Other benefits of his and other deep-water condenser OTEC propositions like TG are decreased movements of both warm and cold water, lessened ecological damage when cold water remains in deep water, smaller pipe diameters, and more minor pumping losses with the movement of 2 orders of magnitude less working fluid.

Prueitt assumed that for a heat channel with an inside diameter of 1.128 m (a cross-sectional area of 1 m^2), a vapor velocity of 75 m/s would transfer surface heat into the deep. Whereas the diameter of an equivalent capacity conventional OTEC plant is 10 m, and Rong-Hua Yeh et al. assumed the velocity flow of cold water in CWP of such a plant was about one m/s [42].

CWP heat transfer is achieved through the sensible heat of water compared to the conveyance of the latent heat of a working fluid in a heat pipe. This conveyance is at a speed approaching that of sound owing to the pressure produced by the boiling of the working fluid and then the vacuum produced when the working fluid vapor is condensed by the deepwater heat sink. The size differential (about one order less for the heat pipe) between the two pipe designs results in a 33% cost savings for the heat pipe [43].

OTEC's ΔT, its efficiency, is increasing annually since global warming is primarily a surface effect, and the temperature increase occasioned by global warming in deep water is almost imperceptible.

7. The TG engineering

Paul Curto, former chief technologist with NASA, described OTEC as "by far the most balanced means to face the challenge of global warming. It is also the one that requires the greatest investment to meet its potential. It is a most intriguing answer that can save us from Armageddon" [43].

With recent technical advancements, this investment can be halved. Heat exchangers represent between about 30% and 50% of the total capital cost of an OTEC system [44]. A US Navy report for a brazed aluminum evaporator with fins on the ammonia passage side of 13,905 m^2 of heat transfer area and a titanium shell and tube condenser with twisted tubes and 13,225 m^2 of total heat transfer area are \$561/m^2 and \$770/m^2, respectively [45]. Whereas the TFHX of Makai Ocean Engineering is projected to cost < \$300/m^2, and power can be produced in 1/10th the heat exchanger volume, leading to significantly reduced labor and overhead costs, plus increased speed of fabrication.

Beyond cost, conventional OTEC is plagued by several issues. First, as **Figure 6** demonstrates, the heat from condenser wastewater is released within the ocean's mixed layer, so it is statistically back at the surface within about three months. Therefore, heat conversion to work provides little climate respite. More importantly, at the energy capacity of TG's potential, 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, per **Figure 8**.

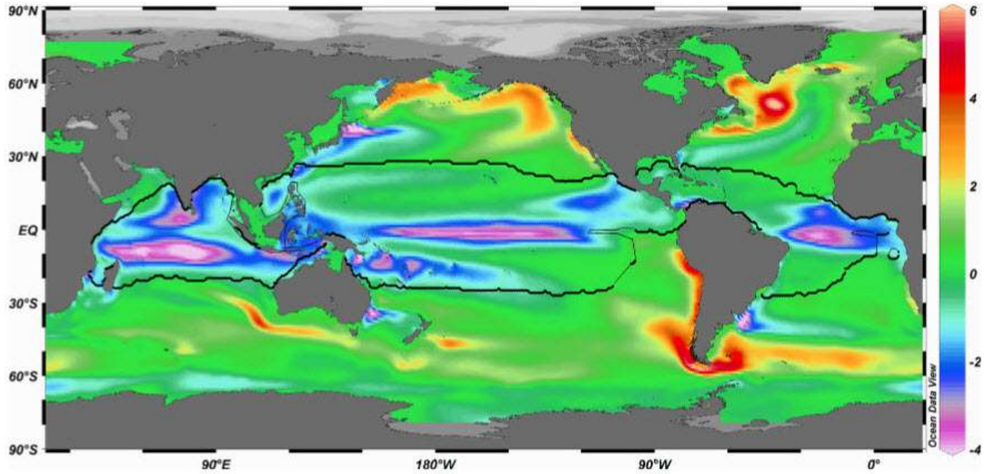


Figure 8. The long-term (1000-year averaged temperature change (°C) in the surface layers (55 m) within the OTEC region outlined by the black line) [31].

The upwelled cold water in **Figure 6** is a dilution of the warm surface, which is only 2.5% of the total ocean volume. To deliver 31 TWyr of power with conventional OTEC, about 62,000,000 m^3/s of cold water would have to be transferred from 1000 m to near the surface, which is 62 Sv. Meanwhile, the thermohaline circulation, the global conveyor belt, which is essential to the rate of sea ice formation near the poles and, in turn, affects other aspects of the climate system, such as albedo, circulates only 15 Sv [46]. The consequence of shifting the volume of water conventional OTEC requires is not only the dilution of the OTEC resource, but upwelled water also pushes surface heat out of the OTEC zone towards the poles, where it becomes both energy and an even more significant environmental hazard, considering surface area declines from the equator poleward. As a result, the Arctic is warming 3 to 4 times faster than at the equator [47]. With conventional OTEC, cold water must be cycled about 3300 times from the depths to the surface over 1000 years. Whereas with TG, heated water would diffuse water from a depth of 1000 m 4.4 times (1000 years/226 years) at a rate of 62,000,000 m^3/(226 years × 365 days × 24 h × 60 min × 60 s)) or about 0.0008 Sv.

The British architect and inventor Dominic Michaelis invented the low-level condenser for OTEC and Energy Island [48]. The latter is a hybrid approach to producing energy from the ocean. His hexagonal platforms were designed to combine wind turbines, solar collectors, wave energy converters, and sea current turbines to produce 250 MW of energy from the water and wind flowing beneath and around the islands.

The 250 MW hexagons are interlockable to scale to higher capacities.

Each hexagon has sides of 291 m, creating a surface area of 220,000 m^2 that is segmented into six equilateral triangles. 19% of the power produced by these hexagons comes from ancillary sources, with the bulk of the energy derived from OTEC (**Table 1**).

Table 1. Energy sources derived from a 250 MW energy island.

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 islands are stationary, whereas grazing the oceans in search of the highest sea surface temperatures (SST) requires mobility, which is facilitated by a triangular shape, as shown in **Figure 9**, that enables a TG platform to cut through the water. A frontal area is obligatory for collecting the heat of warming, but drag impedes the locomotion needed to locate the highest SSTs. The chevron-shaped leading edge shown in **Figure 9** reduces drag while providing twice the frontal area of the base of the TG triangle.

Legend
1. Command center
2. Spinnakers for downwind motivation
3. Solar panels
4. Wave accumulators (in yellow)
5. Horizontal windmills (blue)
6. Hydrogen tanks
7. Evaporators (not shown beneath solar panels)
8. Heat pipe
9. Return fluid and gas lines

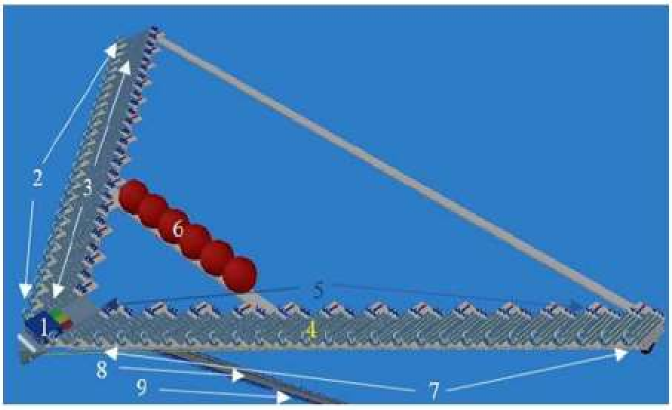


Figure 9. A 1 GW hydrogen-producing TG plant [25].

The real estate behind the leading edge of the TG triangle becomes superfluous unless it can generate more revenue than a void. For example, the National Renewable Energy Laboratory found the total functional wind farm is about 250,000 m^2/MW, and the total land required for 1 MW for generating 200 MW of solar PV power is approximately 4 acres, which is equivalent to 16,000 m^2 [49,50].

An equilateral triangle with sides of 884 m has an area of 338,000 m^3, which, prorated at the ratio of **Table 1**, theoretically could generate 28 MW of wind, 9 MW of wave, and 21 MW of solar power for a total of 58 MW. Whereas a 1 GW TG plant uses only 28,214 m^2 of the ocean's surface and uses 368,082 m^3 of water for its evaporators. With 8.5 m of front and back overhangs of the evaporators, it produces 1 GW, including a combined 5 MW of wind, solar, and wave power from the 42,900 m^2

area of the TG chevron. This is about 70% of the impetus required to move the platform at a speed of about 2 knots as is required to force water through the evaporators and the condensers, which are dragged at 45° below the surface at a depth of 1000 m. The remaining 30% of the propulsive energy can be produced from solar, wind, and wave apparatus situated along the base of the triangle. So, any real estate over and above 42,900 m^2 is precious oceanfront property that is better used for something more productive than producing energy from wind or solar.

If it typically takes 16,000 m^2 to produce 1 MW with PV panels, then TG, at only 42,900 m^2 and 1 GW, is 373 times the solar concentrator of PV panels and is about 5800 times more efficient at using ocean real estate as wind power.

It is estimated that the production of 1 MW of electricity requires four m^3/s of warm water flowing through the evaporators and two m^3/s of cold water flowing through the condensers of an OTEC system [51]. With conventional OTEC, the impetus for this flow is provided by pumps, but for TG heat exchangers, water flow must be provided by the kinetic energy of thrusters situated at each corner of the base of the TG triangle.

The formula for KE is: $KE = 1/2 \times m \times v^2$.

For 1 GW of TG power, 4000 m^3 of water (1000 kg × 4000 m^3) has to flow through the evaporator at a speed of 2 knots (about 1 meter/second), so the requisite KE requirement is 2,000,000 kg × 1 m/s × 1 m/s = 2,000,000 $kg \cdot m^2/s^2$, which is a force of 2,000,000 Joules (J).

Since the condensers need half as much KE flowing through them as the evaporators, the total kinetic energy requirement is 3,000,000 J. Since 1 J is equivalent to 2.7778×10^{-10} MWh, and 3,000,000 J is equivalent to 7.3 MW, then that is the energy requirement (8.33×10^{-4} MWh × 365 days × 24 h) to move a 1 GW plant through the water at a speed of 2 knots. This represents a less than 1% parasitic loss to the TG system and a demonstration of the parsimonious usage of the necessary ocean real estate required to produce 1 GW with a robust, triangular-shaped nautical structure.

This 7.6 MW is the maximum power produced by the ancillary energy sources and is sufficient to move the TG system under its own power from a non-OTEC-producing region into one of the OTEC-producing regions shown in **Figure 3**.

Much of the subsurface TG infrastructure will be filled with working fluid vapor that makes them buoyant, which must be overcome by heavy structures like electrolyzers, generators, ballast, or dive planes that keep the subsurface at the operational depth of 1000 m.

8. Fusion energy

Proponents of fusion energy promote it as energy's Holy Grail [52]. For the purposes of this paper, however, it is a proxy for all exothermic energy sources that are ultimately an impediment to the survival prospects of all living organisms.

Fusion is the source of the Sun's energy and, by extension, is the source of most of the energy found on Earth. It is the combination of lighter atomic nuclei that forms a heavier nucleus, thereby releasing energy. The total mass of the new atom is less than that of the two that formed it, and the "missing" mass is given off as energy, as described by Albert Einstein in his $E = mc^2$ equation, where "c" is the speed of light. Fusion can be an abundant energy source on Earth because it releases significantly more energy per unit of fuel than fission or chemical reactions. It produces no GHGs during operations and less radioactive waste than fission. The waste products are generally less hazardous and have shorter half-lives than the byproducts of fission. It is inherently safe because if containment of the high temperatures and pressures required to sustain the fusion reaction is breached, the reaction immediately stops.

The primary international effort researching fusion power is ITER, which is a collaboration of 35 countries with contrasting political philosophies that bridge the North/South, otherwise seldom spanned, divide between the developed and developing nations [53]. It is, therefore, an exemplar of how global warming could be tackled, but for the problem of waste heat. It is a large-scale scientific collaboration aimed at demonstrating the feasibility of fusion energy for peaceful purposes and a peaceful demonstration of how the dual problems of emissions and global warming can be addressed.

Fusion energy, however, is a highly exothermic method of producing energy, a thermodynamic dead end, and an accelerant of species extinction. It is confronted by significant technological challenges and complexity, including high initial research, development, and construction costs, a lengthy and uncertain timeline to commercialization, the difficulty in achieving net positive energy gain, and a limited supply of tritium, which every fusion reactor will require on the order of 100 to 200 kg per year. Between a gram and a couple of kilograms of tritium are produced each year in the upper atmosphere when cosmic rays strike nitrogen molecules in the air [53]. A few dozen kilograms are also dissolved in oceans as a result of atmospheric nuclear testing carried out between 1945 and 1980. CANDU-type nuclear reactors, of which 31 are currently in operation, supply about 20 kg of tritium a year [54]. Tritium was produced in large quantities by nuclear weapons programs in the US and Russia, which have been heavily curtailed since 1991, but the half-life of the radioactive isotope tritium is 12.33 years, so this supply is rapidly depleting. ITER has about 15 years of tritium for its deuterium-tritium campaign. However, tritium can be produced (bred) during the fusion reaction through contact with lithium, so its supply could be ensured if the technology's other problems, including waste heat, which confront all exothermic energy sources, could be addressed.

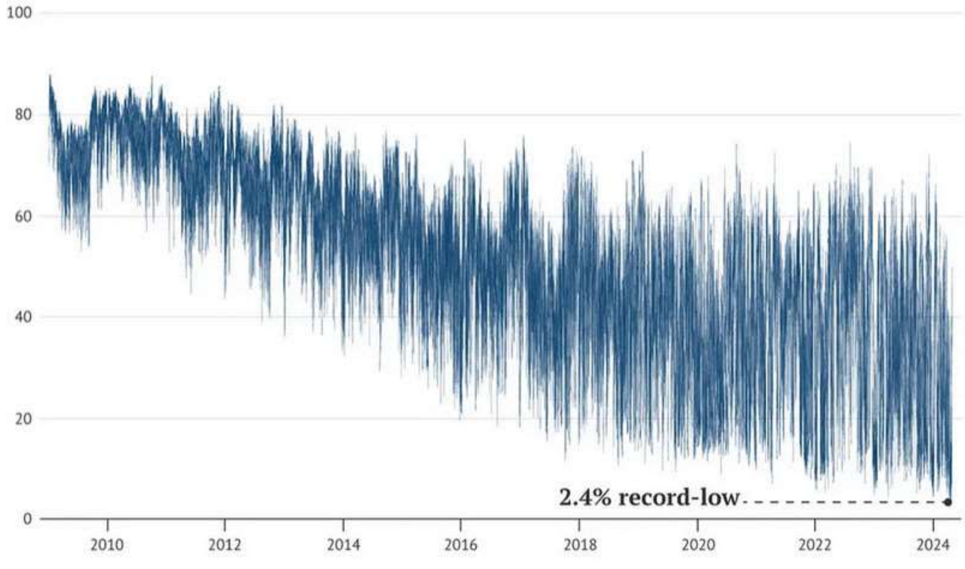
However, the problem of waste heat cannot be wished away. An AI analysis of the efficiency of converting fusion energy into electricity suggests that it is generally lower than that of conventional fission reactors, primarily due to the additional complexities of maintaining and controlling the plasma, which entails efficiency losses of around 30%–50%. Although the Carnot efficiency of a high-temperature fusion reactor is around 40%–50%, the real-world efficiency" is closer to 30%–40%, leaving a combined efficiency of between about 20%–30%. So, at least three times more heat is added to the Earth's system for each TWyr of fusion energy produced.

Thomas Murphy estimates that the waste heat of current energy consumption is about four orders of magnitude smaller than the incident radiation of the Sun, but at a growth factor of ten per century (a modest growth rate of 2.3% per year), waste heat would reach parity with the intensity of the Sun in roughly 400 years [55]. The current EEI associated with climate change is ~1 W m^{-2}, but at a 2.3% energy growth rate, the waste heat of exothermic energy sources would equal the current EEI in 100 years, after which waste heat would become the dominant forcing.

Like all species, humans will soon be at thermodynamic risk of extinction, deriving our energy from exothermic reactions like fusion.

9. Intermittence

Figure 10 shows the share of Great Britain's electricity derived from fossil fuels between 2009–2024.



Source: National Grid Electricity System Operator.

Figure 10. The percentage share of Great Britain's share of electricity derived from fossil fuels in each half-hour period between 2009–2024 [56].

Not only does this graphic show that in April of 2024, the country temporarily derived only 2.4% of its electricity from fossil fuels, it demonstrates that the nation's fossil fuel phase-out has been accompanied by a massive increase in the fluctuation of its energy supply. Ten years ago, these fluctuations were in the range of 20%, but they are now closer to 60%, which is a significant strain on the country's electrical grid. Moreover, Great Britain is not alone in this respect. Europe, South Australia, Texas, and California have similar problems integrating renewables into their grids due to an insufficiency of backup and flexibility of energy sources that can lead to blackouts or brownouts and add costs to grid operators that are then passed on to the consumers of their energy [57–60].

These costs include energy storage, grid management and upgrades, backup generation, curtailment (when excess energy cannot be used or stored), market and regulatory costs, reactive power compensation, and spinning reserve costs that arise due to the fluctuation of weather, time of day, or seasonal variation. Costs that stem from the need to manage the variability and ensure a reliable and stable power grid.

Approximately 40% of global CO_2 emissions are emitted from electricity generation through the combustion of fossil fuels to generate heat to power steam turbines [61]. Replacing fossil fuels with solar and wind generation for the purpose of producing electricity will require either "overbuilding" (i.e., excess annual generation), the introduction of large-scale energy storage, and/or aggregating resources across multinational regions [62]. So even if we had a better electric sector tomorrow, within decades, emissions would be back to where they are today owing to the emissions associated with the overbuilding and the energy storage infrastructure.

10. Energy and the law of supply and demand

As above, there is no shortage of energy to supply the current 22 TWyr of annual consumption. At least for the next 60 years, as the finite energy sources are consumed. Nevertheless, increasingly existing energy consumption is impacting human civilization and other living organisms.

The law of supply and demand is a fundamental economic principle describing the relationship between the availability of a product (its supply) and the desire for that product (its demand) and the effect of that relationship on price, which in the case of this paper relates to the price of energy. When there is excess supply, prices tend to fall until the surplus is eliminated and equilibrium is reached. Conversely, when there is excess demand, prices rise until the shortage is eliminated and equilibrium is reached.

Global warming is a case of a massive oversupply of energy that can be addressed by reducing the excess energy by converting part of it to work and removing the balance from the surface.

In accordance with the law of supply and demand, the consumption of this excess energy will reduce its cost and everything that relies on its consumption.

11. Resources

One of the weighty obstacles to the fulfillment of maximized sustainable energy consumption is material supply, which is another problem the oceans can address. The Energy Transition Commission estimates that between 2022–2050, an energy transition predicated on a 15-fold increase in wind and a 25-fold increase in solar energy to 15 and 34 TW, respectively (which they perplexingly estimate would be 110,000 TWh—about 1/4th of 49 TW), could require the production of 6.5 billion tonnes of end-use materials, 95% of which would be steel, copper, and aluminum, and smaller quantities of critical minerals/materials like lithium, cobalt, graphite, or rare earths [63]. And would require a significant reliance on recycling, innovation, and efficiency improvements.

There are sufficient resources to meet the current demand for 22 TWyr of energy, but 31 TW, as would be required to change the heat of global warming into work, would impose a 40% greater material burden. Furthermore, 49 TWyr would be 158% more than that.

Recycling can reduce the need for mining of materials, but, as the 6th law of thermodynamics proposes, energy, which is always consumed in recycling, degrades the concentration of materials, the quantity of which is also decreased in each successive step in a series of energy transformations.

Advances in technology and efficiency have been offered as a means of reducing the material intensity of renewable energy systems, but as Heun and Brockway in their paper "Meeting 2030 primary energy and economic growth goals: Mission impossible?" suggest, energy efficiency is not an effective means of reducing primary energy consumption [64].

IRENA lists the necessary materials for an energy transition as: lithium, cobalt, nickel, graphite, manganese, iron, phosphorus, aluminum, copper, silver, and gold [65]. Although they are not listed in IRENA's list, magnesium and calcium are the second and third most abundant minerals in the ocean and are ideal for the manufacture of a significant portion of TG infrastructure.

Phosphorous is not found in abundance in the oceans, nor is graphite, except for that which is produced near thermal vents associated with tectonic plate boundaries, and iron and aluminum are less abundant in the ocean than on land, but otherwise the oceans are a cornucopia of minerals and metals that could provide many centuries worth of supply of the materials needed to deliver centuries worth of renewable energy with TG per **Table 2**.

Table 2. Elements etc.

a	b	c	d	e	f	g	h	i	j
Element	**Conc in SW**	**Vol of ocean**	**Ocean**	**Land**	**Yrs supply**	**Mined/yr**	**Yrs land**	**Yrs ocean**	**Multiple**
	(ppm)	**liters**	**MM (tonnes)**	**MM (tonnes)**	**Oceans**	**MM (tonnes)**	**reserves**	**reserves**	**Ocean/Land**
Mg	1290	1.332 × 10^{21}	1,718,280,000,000	64,541,000,000,000	4,909,371,428.6	0.950	67,937,894,736,842	1,808,715,789,474	0.0266231
Ca	411	1.332 × 10^{21}	547,452,000,000	114,955,000,000,000	1,564,148,571.4	0.035	3,284,428,571,428,570	15,641,485,714,286	0.0047623
K	392	1.332 × 10^{21}	522,144,000,000	57,893,000,000,000	1,491,840,000.0	72.000	804,069,444,444	7,252,000,000	0.0090191
Li	0.178	1.332 × 10^{21}	237,096,000	55,400,000,000	677,417.1	0.106	522,641,509,434	2,236,754,717	0.0042797
Ni	0.0066	1.332 × 10^{21}	8,791,200	232,680,000,000	25,117.7	2.700	86,177,777,778	3,256,000	0.0000378
Fe	0.034	1.332 × 10^{21}	45,288,000	155,951,000,000,000	129,394.3	2600.000	59,981,153,846	17,418	0.0000003
Al	0.001	1.332 × 10^{21}	1,332,000	229,910,000,000,000	3805.7	68.000	3,381,029,411,765	19.58	0.0000000
Cu	0.0009	1.332 × 10^{21}	1,198,800	166,200,000,000	3425.1	21.000	7,914,285,714	57,086	0.0000072
Mn	0.0004	1.332 × 10^{21}	532,800	2,631,500,000,000	1522.3	20.000	131,575,000,000	26,640	0.0000002
Co	0.00039	1.332 × 10^{21}	519,480	69,250,000,000	1484.2	0.170	407,352,941,176	3,055,765	0.0000075
Ag	0.0003	1.332 × 10^{21}	399,600	20,775,000,000	1141.7	0.026	799,038,461,538	15,369,231	0.0000192
Au	0.000011	1.332 × 10^{21}	14,652	11,080,000	41.9	0.003	3,574,193,548	4,726,452	0.0013224

(a) Elements, (b) Concentration of elements in seawater (ppm), (c) Volume of the ocean (liters), (d) Concentration of elements in the ocean in million tonnes = b × c/1000/1000000), (e) Land abundance of elements (million tons) = the weight of crust (27 trillion tonnes/1,000,000) × the percentage of the element in the crust, (f) Yrs supply of elements in the ocean (million tons) = d/350 (1-GW TG plant moves 4000 tonnes/sec of water through its heat exchangers, TGs energy potential is 31 TW, and the ocean's mass is 1.4 quintillion short tons of water; therefore 31,000 1-GW plants could move the ocean's total mass through it heat exchangers in about 350 years), (g) Mined each year in million tonnes, (h) Current yearly consumption of elements (tons) = e/g, (i) Yrs ocean reserves = d/g, and (j) Multiple of Ocean/Land = i/h [66–70].

Although **Table 2** indicates there are about 192 times more of the elements in the earth's crust than in the ocean, it is physically impossible to mine and process all the minerals in the crust. Meanwhile, 31,000 TG plants would pass the total volume of the oceans through their heat exchangers in about 350 years. As an example of the recoverability of a vital mineral like copper, the United States Geological Survey estimates there are about 870 million tonnes of recoverable reserves [71]. Whereas **Table 2** shows there are 1,198,800 million tonnes of copper dissolved in the ocean, which is about 1400 times the recoverable reserves of the crust. So, if only 1% of the dissolved copper in the ocean could be recovered, it would still be about ten times more than the recoverable land reserves.

Magnesium hydroxide and calcium carbonate are the main components of Biorock, which could be widely used in the manufacture of TG platforms [72]. These compounds are derived from an electrochemical reaction with seawater in which Mg and/or Ca are crystallized at a cathode. Under low electrical current conditions, extremely hard calcium carbonate limestone deposits, made up of crystals of the mineral aragonite, are formed, and higher currents cause the growth of the mineral brucite, or magnesium hydroxide, which is soft.

On a steel, aluminum, or titanium frame, calcium carbonate accretes at a rate of between 1–2 cm per year and has a load-bearing strength about three times ordinary Portland cement. Magnesium hydroxide is soft and flaky and accretes at a similar rate with little load-bearing strength, but it can be cast in molds to form bricks, blocks, or other shapes. However, magnesium hydroxide is readily converted into magnesium carbonate cement by absorbing CO_2, and this cement is even harder than calcium carbonate. Whereas conventional cement manufacturing combusts limestone to make quicklime and releases CO_2 into the atmosphere and is a primary global source of greenhouse gas, biorock cements can be produced on a large scale with energy produced from the conversion of the heat of global warming to work. And these are harder than contemporary cements and reduce global warming by removing CO_2 from the atmosphere and the oceans.

The price of resources is inexorably rising, as are surface temperatures due to fossil fuel burning, and with every degree of warming, the risk of species extinction increases, and massive environmental damage is being done. Humans and other species are migrating to forestall these outcomes, and society is absorbing the environmental costs, all of which can be mitigated with the resources available in the oceans.

The Office of Energy Efficiency & Renewable Energy of the US Department of Energy lists the various methods whereby dissolved seawater minerals and metals can be mined and produced [73].

The heat of global warming is 15 times the energy necessary for a total energy transition that would mitigate every consequence of climate change at 1/6th of the existing cost of energy, which is a rebuttal to the argument that the decoupling of global GDP from resource use is a physical impossibility on a finite planet [25].

12. Energy carriers

Trade in ocean-based goods and services represents about 3% of the global GDP

[74]. To service the other 97%, ocean-derived energy must be conveyed to the land [73].

OTEC converts heat to work, which is initially converted to electricity. Most proposed conventional OTEC operations will be on stationary platforms from which electricity could be conveyed worldwide through an HVDC grid. According to the European Commission, HVDC transmission losses are less than 3% per 1000 km, which is 30 to 40% less than alternating current lines at the same voltage [75]. A 1000-square-kilometer grid of the planet could service every site on the planet.

However, experimental and emerging technologies can also convey power without wires through microwave or laser transmission. These eliminate the need to locate physical infrastructure in remote or difficult-to-access areas and have been offered for space-based solar power applications. As with HVDC transmission, however, converting electricity to microwaves and laser beams and back again involves energy losses, and microwaves and lasers pose safety risks to living organisms.

TG plants cannot be tethered to a grid because they need to be mobile in order to seek out the highest SSTs, so an energy carrier is required. However, producing goods on ocean-going green fields by the conversion of raw materials using ocean-derived electricity or providing services on these green fields is a unique way of energy carrying that TG can provide. As is the recycling of worn-out goods and materials into new materials on ocean-going green fields using ocean-derived electricity.

To reduce the dependence on fossil fuels, particularly in the transportation sector, for electricity generation, heating, or cooling, a more conventional energy carrier is required.

As the use of fossil fuels declines and is replaced with energy supplies from non-fossil sources, the world could eventually become oversaturated with electricity and deficient in chemical fuels [76]. Hydrogen is the most elemental chemical and can be derived by the electrolysis of seawater. As the DOE has pointed out, HPE can contribute to the enabling and acceptance of technologies where H_2 is the energy carrier [77]. TG electrolyzers would operate at a depth of 1000 m where the pressure is 100 bar. HPE requires pressures of 120–200 bar at 70 °C, whereas the temperature at 1000 is 4 °C. These temperatures and pressures are conducive to HPE and would eliminate the need for external compression that would otherwise consume about 3% of the energy required for HPE. H_2 produced at 1000 m arrives at the surface 70% of the way, logarithmically, to the 700-bar pressure needed for transportation applications.

Green or renewable H_2 is indispensable to climate neutrality [78]. In theory, it can store excess renewable energy generated during periods of low demand, which can then be converted back into electricity when needed for decarbonizing sectors that are difficult to electrify, such as long-distance transportation and heavy industries like steel and cement production. H_2 can serve as a zero-carbon feedstock in the production of chemicals and synthetic fuels, replacing fossil fuels in the processes.

Ammonia is another energy carrier offered as a chemical replacement for fossil fuels, but ammonia production requires an H_2 precursor plus a costly additional manufacturing step. And the Haber-Bosch process, which accounts for more than 90% of the world's ammonia production, accounts for 1.4% of global carbon dioxide emissions and consumes 1% of the world's total energy production [79].

Magnesium and calcium, as shown in **Table 2**, are plentiful in the oceans and have massive energy-carrying potential. Magnesium hydride has a high energy density and can store H_2 that can be released as needed. It is a candidate for H_2 storage in renewable energy systems. Magnesium-ion batteries are being researched as a potential alternative to lithium-ion batteries due to magnesium's abundance, safety, and energy density [80]. These batteries use magnesium as the anode and oxygen from the air as the cathode. They have high theoretical energy densities and are being explored for long-term energy storage and electric vehicles.

Magnesium in a high-oxygen environment can be combusted to produce heat, light, electricity, and magnesium oxide that can be recycled back into magnesium, forming a closed system loop.

Calcium can also serve as an energy carrier in the context of calcium-ion batteries and other chemical energy storage systems. Calcium-ion batteries are also being researched as an alternative to lithium-ion batteries given their potential to offer high voltage and energy density [81]. Calcium hydride reacts with water to produce H_2 gas that can then be used as a fuel or stored for later use. Calcium can also be used in thermochemical energy storage processes, where it undergoes reversible chemical reactions to store and release energy. For example, calcium oxide reacts with water to form calcium hydroxide while releasing heat that can be used for various applications, such as power generation. Calcium-based systems are generally considered safe and non-toxic, and calcium-based compounds can offer high energy densities, making them efficient for storing and transporting energy.

The development of magnesium and calcium-based energies and their storage are in their early stages of development and face significant challenges, but in view of the abundance of these metals in the ocean, such development is worth pursuing, considering the vital role energy carriers can provide, conveying ocean-derived energy to land-based consumers.

13. Conclusions

As reviewed, TG presents a large, continuous, renewable energy resource that can contribute to the reduction of global warming by converting a portion of that heat to work and relocating the balance into deepwater from where it will return and can be recycled. Energy is vital to all living organisms, but beyond the human species' need for energy is an economic imperative. Both of which are melded into a proposed 7th Law of Thermodynamics that combines the MPP with the Law of Supply and Demand completing the suite of thermodynamic laws. Thereby unifying them into a general solution to one of humanity's greatest concerns. Over 90% of the heat of warming is going into the oceans, which is a reasonably recoverable reserve that can be recovered under current technological and economic conditions. OTEC is the technology whereby this reserve can be harvested. It is the embodiment of ocean thermal dams that converts the stratified heat of the tropical surface into work in accordance with the second law of thermodynamics. TG is the improvement that increases conventional OTEC's thermodynamic efficiency, thereby allowing it to produce about two and a half times more energy. It is a dissection of the global heat engine into manageable tranches. And is an endothermic resource that derives heat from its environment, thereby negating the thermodynamic consequence of waste heat while reducing the cost of energy production and of everything that relies on energy inputs. The oceans contain a wealth of dissolved minerals and metals that can supply a renewable energy transition and produce energy carriers that can convey ocean-derived power to land-based consumers. TG "is a true triple threat against global warming. It is the only technology that acts to reduce the temperature of the ocean directly, eliminates carbon emissions, and increases carbon dioxide absorption while generating portable and efficient fuel. It can create millions of jobs and is a serious contender for the future multi-trillion-dollar energy economy. It is baseload negative emission technology that would yield the lowest social costs and should be prioritized for investment." [43] It is the maximum utilization of the ocean's stored thermal energy and can maximize the utilization of its mineral resources. Whereas artificial intelligence is being offered as a tool for fighting climate change by predicting weather, tracking icebergs, and identifying pollution, OTEC is anthropogenic intelligence that can ensure the survival of our species with direct climate cooling and the intelligent use of the ocean's resources and is the only near-term option available for limiting global warming and moderating its devastating consequences [28].

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Conflict of interest: The author declares no conflict of interest.

Nomenclature

CO_2	carbon dioxide
CWP	cold-water pipe
EEI	Earth's energy imbalance
PE	gravitational potential
GHGs	greenhouse gases
GDP	Gross domestic product
HPE	high-pressure electrolysis
HVDC	high-voltage direct current
H_2	Hydrogen gas
ITER	International Thermonuclear Experimental Reactor
kcal	kilocalories
kgf-m	kilogram-force meter
KE	kinetic energy
m	mass in kilograms
MPP	maximum power principle
MEER	Mirrors for Earth's Energy Rebalancing
OTEC	ocean thermal energy conversion
O_2	Oxygen gas
Sv	Sverdrup - unit of volumetric flow rate equal to 1 million cubic meters per second

Twyr_{30}	terawatts-years in the 30-year time frame considered for renewables and consumption
Twyr	terawatts -years
TG	thermodynamic geoengineering
TFHX	thin film heat exchangers
GESAMP	UN’s Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection
UNFCCC	United Nations Framework Convention on Climate Change
DOE	US Department of Energy
v	velocity in meters/sec
W/m^2	watts per meter squared

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