

## Negative-CO<sub>2</sub>-emissions ocean thermal energy conversion

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### ABSTRACT

Conversion of the ocean's vertical thermal energy gradient to electricity via Ocean Thermal Energy Conversion (OTEC) has been demonstrated at small scales over the past century, and represents one of the largest (and growing) potential energy sources on the planet. Here we describe how OTEC could be modified to provide a large source of CO<sub>2</sub>-emissions-negative energy while also allowing heat removal from the surface ocean, helping to directly counter ocean/atmosphere warming. Most OTEC energy potential is far offshore, thus the conversion of the produced electricity to a chemical energy carrier such as H<sub>2</sub> or derivatives is required. This can be achieved by employing a method of electrochemically generating H<sub>2</sub> that also consumes CO<sub>2</sub>, converting the carbon to a common form of ocean alkalinity. The addition of such alkalinity to the ocean would provide high-capacity carbon storage while countering the chemical and biological effects of ocean acidification. For each gigawatt (GW) of continuous electric power generated over one year by the preceding negative-emissions OTEC (NEOTEC), roughly 13 GW of surface ocean heat would be directly removed to deep water, while producing  $1.3 \times 10^5$  tonnes of H<sub>2</sub>/yr (avoiding  $1.1 \times 10^6$  tonnes of CO<sub>2</sub> emissions/yr), and consuming and storing (as dissolved mineral bicarbonate) approximately  $5 \times 10^6$  tonnes CO<sub>2</sub>/yr. The preceding CO<sub>2</sub> mitigation would result in an indirect planetary cooling effect of about 2.6 GW. Such negative-emissions energy production and global warming mitigation would avoid the biophysical and land use limitations posed by methods that rely on terrestrial biology.

### 1. Introduction

The 2015 Paris Agreement is an important step toward limiting global warming to less than 2 °C, with a stated desire to further limit the temperature increase to 1.5 °C above pre-industrial levels [1]. In this effort, it was agreed to unleash actions and investment that reduce greenhouse gas (GHG) emissions, principally CO<sub>2</sub>, and to enhance GHG sinks. By the time the agreement was reached measurements indicated that the 1-degree mark had already been surpassed (Fig. 1) and thus the world community has already exceeded two-thirds of its aspirational warming quota. At an estimated warming rate of  $0.25 \pm 0.05$  °C per decade by 2020 [2] there are only about 20 years left to act if we are to avoid its worst consequences of global warming, considering that long-term equilibrium temperatures will not have been reached by that time [3]. Nor is warming the only effect of elevated atmospheric CO<sub>2</sub>. Via the passive diffusion of excess CO<sub>2</sub> into the ocean and the spontaneous formation of carbonic acid, surface ocean acidity has increased more than 30% since pre-industrial times and continues to increase [4]. This has the potential to greatly alter marine biogeochemistry and ecosystems, and the goods and services they provide [4].

Thus far the primary action taken to avoid dangerous climate change and ocean acidification has focused on reducing GHG emissions, particularly replacement of fossil with non-fossil energy and by decarbonization of fossil energy, for example via carbon capture and storage, CCS. However, it is now acknowledged that the pace of these actions, especially in the face of growing energy demand will very likely be insufficient to keep global warming below 2 °C, and most certainly below 1.5 °C [3]. To reconcile these shortcomings, modeling studies have found it necessary to include proactive removal of CO<sub>2</sub> from the atmosphere or enhancement of carbon retention in sinks, i.e., negative emissions [3,7,8]. The quantities of atmospheric CO<sub>2</sub> removal required ranges from less than 100–1000's of Gt, depending on the success of the emissions reduction and the mean global temperature objective [8]. While natural processes currently remove some 20 Gt of CO<sub>2</sub>/yr from the atmosphere [9], no method of significantly increasing this quantity has been demonstrated at scale. Potential negative-emissions methods receiving the most attention employ land plants by increasing their collective uptake and/or storage of carbon e.g., afforestation, biochar, or biomass energy coupled with carbon capture and storage (BECCS) [7,9]. BECCS has received particular interest because it generates

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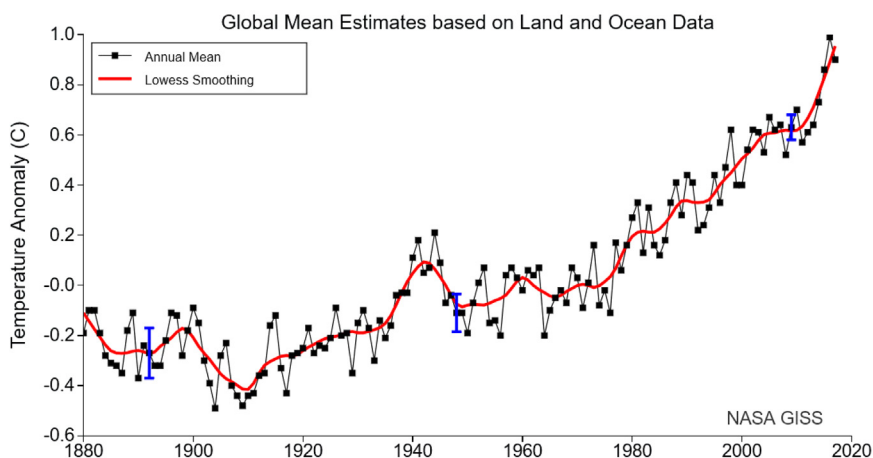


Fig. 1. Land-ocean temperature index, 1880 to present, with reference period 1951–1980. The solid black line connects the global annual means and the solid red line is a smoothed fit. The blue uncertainty bars (95% confidence limit) account only for incomplete spatial sampling. Source: refs. 5,6. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

renewable energy via conventional biomass combustion in a power plant while storing the resulting  $\text{CO}_2$  underground, thus securing the carbon from returning to the atmosphere as it eventually would under natural circumstances. However, the use of land plants for such negative-emissions schemes is challenged by the biophysical limits imposed by the required land, water, and nutrient use, especially in competition with the growing demand for food, fiber and fuel [10–12].

For these reasons, it would be advantageous to couple additional and globally far larger renewable energy sources with atmospheric  $\text{CO}_2$  removal beyond that offered by BECCS. It has been shown that mineral weathering (a major natural  $\text{CO}_2$  absorber [13]) can be integrated into and greatly accelerated during the electrochemical production of  $\text{H}_2$  at modest energy penalty [14–17]. When powered by renewable electricity these systems can consume approximately 20–40 tonnes of  $\text{CO}_2$  per tonne of  $\text{H}_2$  generated depending on whether carbonate or silicate minerals are used in the process, and whether carbonates or bicarbonates are produced. Thus, in addition to reducing  $\text{CO}_2$  emissions via substitution of conventional, fossil-fuel-derived  $\text{H}_2$  with the preceding electrochemically derived  $\text{H}_2$ , the process produces a strongly  $\text{CO}_2$ -emissions-negative fuel or chemical feedstock. Given the global abundance of the base minerals and salt electrolyte required, the scale of the process might only be limited by the cost and availability of non-fossil-derived electricity. While any source of such electricity can be utilized (solar, wind, wave, tidal, biomass, nuclear, etc.), the case for that generated from Ocean Thermal Energy Conversion, OTEC, is especially compelling.

## 2. OTEC as an energy source

Conventional OTEC uses warm surface water in an evaporator to boil a low-boiling-point working fluid such as ammonia or haloalkane refrigerants to produce a vapor that powers a turbine generator. The spent vapor is then condensed back to a fluid via heat exchange with cold seawater pumped from a depth of some 1000 m. The mixed seawater from both the evaporator and condenser are then discharged at a depth of 60–100 m. OTEC requires a minimum temperature differential between the surface and deeper water of  $20^\circ\text{C}$ , characteristic of an area that covers about one third of the global ocean between the latitudes  $30^\circ$  degrees north and south of the equator (Fig. 2). While theoretical Carnot energy conversion efficiencies for conventional OTEC range from 6% to 8%, realized efficiencies of conventional designs are typically half of these values [19,20]. As we will discuss, various ways of increasing these efficiencies can be considered. By one estimate [21] some 228 terawatts (TW) of primary power are available on or in the ocean, the vast majority of which is represented by the significant thermal gradient between the surface and deep ocean. However, considering OTEC's low energy conversion efficiency and the need to

minimize effects on oceanic thermohaline circulation (THC), the physical maximum conventional OTEC potential appears to be about  $25 \text{ TW}_e$  [22], still making it globally the largest, near-continuous renewable energy source available (Table 1).

Furthermore, the energy potential of OTEC is increasing due to global warming. Surface ocean warming dominates the increase in anthropogenic thermal energy stored in the climate system, accounting for more than 90% of the energy accumulated between 1971 and 2010 [7], with two-thirds of this heat accumulating in the upper 700 m of the oceans [26]. In the past 18 years, the oceans have accumulated as much heat as they did in the prior 133 years. When this large and growing upper ocean heat source is coupled, via the use of Rankine-cycle-based OTEC, to the vast heat sink below the thermocline, it presents the opportunity to produce very significant quantities of primary energy.

The world total primary power consumption is approximately 18 TW (Table 1), 81% (15 TW) of which is derived from fossil fuels [25]. The urgency with which we need to replace this fossil energy with zero emissions sources, especially those that can supply energy constantly (Table 1), makes OTEC's actual energy delivery potential highly relevant.

## 3. Beneficial surface ocean cooling

The operation of conventional OTEC in effect draws heat from the surface ocean to perform work and discharges the remaining heat at a deeper depth in a manner that does not degrade the required ocean thermal gradient for OTEC. The climate benefit that can be derived by manmade transfers of heat from the ocean's surface to the interior is evident from the apparent hiatus in atmospheric warming experienced between 1998 and 2013 [27]. The observed rate of warming during that period was only  $0.04^\circ\text{C}$  per decade, whereas for the period 1990–2012 that rate was about  $0.21^\circ\text{C}$  per decade [28]. Since  $\text{CO}_2$  concentrations continued to rise during this period and net heat losses from the top of the atmosphere cannot explain the hiatus, the heat content of the Earth system must have continued to increase with the heat ending up in the ocean. Gleckler et al. [26] affirm that an unexpectedly large heat transfer to the subsurface ocean occurred during this period and was the principal reason for the marked attenuation of global surface atmospheric warming. Subsequently, atmospheric warming resumed once the Pacific overturning cell that sequestered the shallow heat reversed, releasing heat that had been located down to a depth of about 300 m back to the surface [29]. This implies that any additional heat transfer to the deep ocean offered by OTEC would help mitigate at least some of the surface ocean and atmospheric warming and associated negative climate and environmental impacts. This includes a reduction in the rate of sea level rise (the coefficient of expansion of seawater at 1000 m is half that of the tropical surface water,

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