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Downdraft energy tower for negative emissions: Analysis on methane removal and other co-benefits

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Abstract: The downdraft energy tower is proposed in research as a new technology for green electricity in recent years. In this work, it is analyzed as an emerging greenhouse gas removal technology against climate change that provides multiple co-benefits for the environment, in addition to green electricity. Compared to other negative emission technologies, DET might be able to remove atmospheric methane (CH_4) without adding additional equipment, materials or costs. In multiple case studies, the DET offers at least 15% increase in profit thanks to CH_4 removal in addition to green electricity generation. © 2023 The Authors. *Greenhouse Gases: Science and Technology* published by Society of Chemical Industry and John Wiley & Sons Ltd.

Keywords: downdraft energy tower; economic benefits; methane removal; negative emission

Introduction

The Paris Agreement, ratified in 2016, aims to limit global warming to below 2°C above pre-industrial levels and pursues efforts to limit warming to 1.5°C.[1] However, the current trajectory of emissions reduction has fallen short of the targets set by the Paris Agreement.[2] The planet's long-term warming trend continues, with global temperatures in 2022 being 0.89°C above the average for NASA's (National Aeronautics and Space Administration) baseline period (1951-1980).

In November 2022, the global monthly mean carbon dioxide (CO_2) was recorded at 417.8 parts per million (ppm), with yearly rise of 2.21 ppm.[3] Similarly, methane (CH_4) levels in the atmosphere have also been increasing, with the global average concentration of about 1,895 parts per billion (ppb) at the end of 2021. In November 2022, the CH_4 levels have surpassed 1,923 ppb.[4] Despite efforts by countries to reduce

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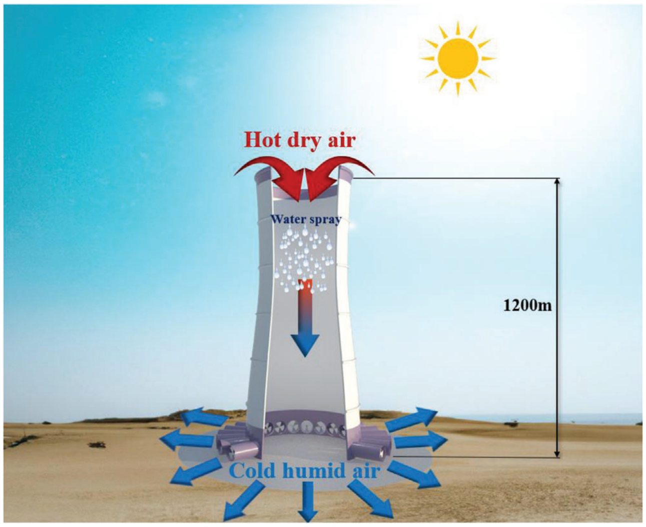

Figure 1. Illustration of working downdraft solar energy tower.

emissions, global emissions continue to rise.

Therefore, reducing emissions of CO_2 and CH_4 is crucial for slowing down the warming of the planet and avoiding the worst impacts of climate change. It prompted a renewed focus on clean energy, with countries exploring alternatives to traditional fossil fuels. One such technology is the downdraft energy tower (DET, as illustrated in Fig. 1), a power plant that harnesses solar energy to generate electricity.[5] This renewable energy source is considered environmentally friendly as it does not release greenhouse gases (GHGs) or pollutants that contribute to global warming, thus reducing dependence on fossil fuels and mitigating the effects of climate change.[5]

In addition to emissions reduction, greenhouse gas removal technologies, also referred to as negative emissions technologies (NETs), have also been receiving increasing interests as they can provide humanity more powerful tools to tackle the climate challenge. The utilization of DET as a renewable energy source has the added benefit of increasing the humidity levels in the surrounding environment. This in turn can improve the efficiency of removing atmospheric CH_4 via enhanced hydroxyl radical sink,[6] which is the primary natural sink of CH_4. In other words, DET can enhance the natural hydroxyl radical sink without adding equipment, materials (e.g., catalysts, photocatalysts), or costs.

In this work, by analyzing this CH_4 removal co-benefit, we provide insights to understand the removal potential and economic benefits of this technology, which can produce clean energy and also remove atmospheric CH_4. This is a starting point of an exciting research topic and a new negative emission technology. We expect it could serve as a stepping-stone for wider and deeper research into this topic.

Utilizing the downdraft energy tower for electricity generation

The DET is an unusual renewable energy technology that harnesses the power of the hot dry air to generate cold downdraft wind by seawater evaporation to generate electricity using turbines. The power generation process is achieved by building a tall tower in a dry and hot desert area and spraying water from the top of the tower.[7] The water drips down and evaporates, cooling the air inside the tower and making it heavier than the surrounding hot air. This creates a downdraft, caused by the difference in temperature between the hot air and cooled air that can be used to spin a turbine at the base of the tower to generate electricity. This methodology, also known as an aero-electric power station,[8] has been demonstrated to be a viable means of generating electricity.

Gutman's research on DET has made important contributions to the understanding of the technology's potential. Through quantum field theory calculations, they have determined the optimal water jet and turbine speeds under ideal conditions, providing valuable insights into how to maximize the power generation efficiency of DETs.[8] It is estimated that a DET with a height of 1200 m and a diameter of 400 m can generate up to 380 MW of net electricity.[8]

DET performance for CH4 removal

When water droplets with a diameter of 100–200 mm are sprayed on the top of the DET, it is enough to saturate the water vapor in the air.[8] This results in the release of humid air through the fan outlet, which can increase the humidity levels in the surrounding atmosphere. This increase in humidity can have a significant impact on the atmospheric concentration of hydroxyl radicals (represented as °OH), which are continuously formed through the photolysis of ozone (O_3) and water vapor, as shown in Eqns 1 and 2, and Fig. 2.

°OH are highly reactive molecules, acting as an important oxidizer and cleaner of the atmosphere, and

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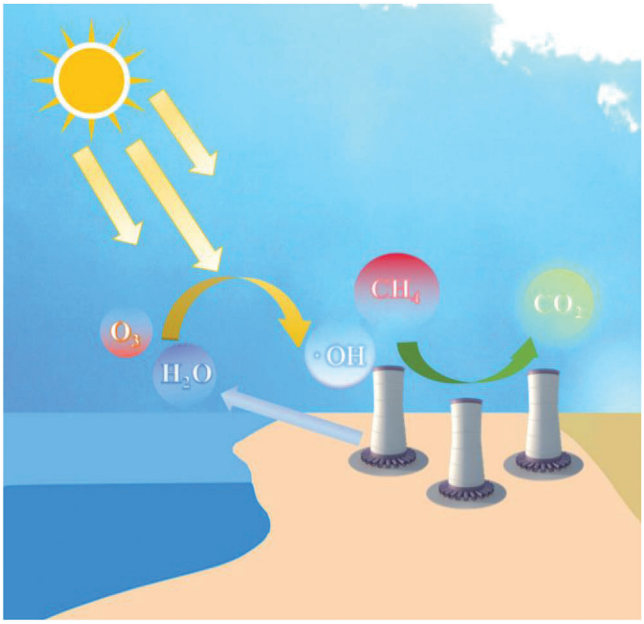

Figure 2. Downdraft solar tower removes CH_4 from atmosphere.

breaking down pollutants and other trace gases (Eqns 3 and 4). It is therefore the main sink for atmospheric CH_4. About 90% of the CH_4 in the atmosphere is removed by hydroxyl radicals.[9] The extra hydroxyl radicals prompted by DET can help reduce the burden of CH_4 (Eqn 5) and O_3 (Eqn 1).

The above description process is mainly as follows:

$$O_3 + h\nu(\lambda < 330\text{nm}) \rightarrow O_2 + O\left(^1D\right) \quad (1)$$

$$O\left(^1D\right) + H_2O \rightarrow 2^{\circ}OH \quad (2)$$

The °OH then react with other atmospheric gases such as CH_4 and other pollutants, breaking them down into simpler molecules:

$$^{\circ}OH + CH_4 \rightarrow H_2O + CH_3 \quad (3)$$

The CH_3 produced in this reaction can then be further oxidized by complex process usually involving multiple reactions and intermediates, such as CH_3O_2 and CH_2O,[10 (pp. 332–335)] and convert to CO_2 finally. In this case, a total of three moles of °OH are required to completely convert one mole of CH_4 into CO_2 considering equation balancing focus on methane-related reaction.

$$4CH_4 + 12^{\circ}OH + 5O_2 + h\nu \rightarrow 4CO_2 + 14H_2O \quad (4)$$

The actual reaction rate will depend on various factors, such as the concentration of CH_4, °OH and other trace gases in the atmosphere, temperature, pressure and humidity, and the presence of other catalysts or inhibitors.

Table 1. The amount of gases pass through or removed by DET per day.

Element	Number	Units
Air mass	2.86×10^8	tons
CO_2	1.81×10^5	tons
O_3	517.3	tons
CH_4	302.3	tons
°OH-production	1.17×10^7	mol
°OH-reaction	2.34×10^6	mol
CH_4 removal	12.5	tons
CH_4 removal-CO_2e	311.4	tons

In this study, we propose an ideal DET with a chimney height of 1200 m and a diameter of 400 m, located in Jordan. The amount of gases pass through or could be removed by DET per day is estimated as given below and summarized in Table 1.

All reactions were carried out under ideal conditions, and the reactions were all complete. Since the bottom air velocity is as high as 80 km/h,[8] the mass of air passing through the DET throughout the day can be calculated by considering the air velocity and the cross-sectional area of the tower using the principle of continuity.

$$Q = \int Aqdt \quad (5)$$

where A is the cross-sectional area of the chimney and q is the velocity of the air passing through this cross-section. Therefore, the air flow through DET is 2.86×10^8 tons per day (i.e., 241 km^3 per day).

According to NOAA, as of 2022, the concentration of CO_2 in the earth's atmosphere is about 417 ppm,[11] the concentration of CH_4 is about 1911 ppb, and the concentration of O_3 varies due to location and altitude, so we take the values of CO_2, CH_4, and O_3 concentrations in the atmosphere as 417, 1.911, and 1 ppm, respectively. Therefore, we can conclude that the mass of CO_2, O_3, and CH_4 passing through DET under ideal conditions are 1.81×10^5, 517.3, and 302.3 tons per day (i.e., 1×10^8, 2.4×10^5, and 4.6×10^5 m^3 per day at 25°C and 1 atm).

The maximum duration of solar radiation in Jordan is about 13 h. According to Eqn 1, DET produces about 198 tons of °OH and about 20% of these °OH oxidizes CH_4,[12,13] which is 12.5 tons per day from the

Table 2. Downdraft energy tower performance estimates.

Location	Height (m)	Diameter (m)	Maximal net power (MW)	Investment ($Bn)	Annual revenue (M$)	Annual profit (M$)	Reference
San Luis	685	152.4	670	1.5	56.18	–	17, and 19
Eilat	1,280	400	411	0.9	272	69	20
Jordan	1,200	400	380	0.7	264.5	68.4	Estimated in this work

atmosphere (i.e., 4.1% of atmospheric CH_4 gas is removed from the air). This equates to a reduction of about 311.4 tons of CO_2e per day taking into account $GWP_{100} = 25$ for CH_4. Based on the estimated total CH_4 emissions of Jordan in 2022, which is 274 kt.[14] b), a single DET can potentially reduce about 1.7% of CH_4 emissions in Jordan.

The °OH budget of 20% towards CH_4 is a global average. In dry and clean desert area, the concentrations of other gases which consume °OH (e.g. CO, VOCs) should be lower than global average.[15,16] At the same time, there are other sources of °OH, which are generated by the photolysis of HNO_2 and H_2O_2.Therefore, the estimation of CH_4 gas consumption by DET in such areas may be conservative, and the actual removal rate may be higher.

Economic benefits of DET

Economic benefit from electricity generation

Several case studies of economic benefits of electricity generation from DET are summarized in the Table 2 below. For example, based on the information provided by KiNRG which plans to build a massive hollow tower reaching 686.4 m in height and 152.4 m in width for a DET in San Luis, Arizona, is projected to have a peak production of 1,950 MWh on sunny days, with an average daily production of 670 MWh when lower production times are taken into account. The company states that construction costs approximately US$1.5 billion, which is one-third of what it costs to build an equivalent solar or wind farm. It can bring back US$56.18 million annual revenues.[17,18]

The results of modeling at a potential location near the city of Eilat may be more informative.[20] The authors have calculated the costs using a model (1280 m high, 400 m diameter tower, 40 km from the sea) with almost similar parameters to the DET system discussed before. The annual cost of the plant includes the initial investment, the operation and maintenance costs and the installation of the pumped energy (electricity) cost components. According to tests, the cost of the plant is 4.17 $/kWh, which is similar to the cost of a fossil fuel power station (i.e., an initial investment of US$ 0.9 billion). The annual revenue is US$ 272 million, the total annual cost is about US$ 203 million, and the annual profit is US$ 69 million. The corresponding internal rate of return is 15.1%.

It is noteworthy that the economic benefits of the DET technology are specific to the locations and specifications used in those studies and may not be directly generalized to other locations or variations in tower size. Therefore, a more general calculation is detailed here based on the model by Gutman et al..[8]

In this case, the DET system can generate 380MW net power (1200 m high, 400 m diameter tower, 40 km from the sea), the investment cost of DET can be calculated as follows:

$$C_{tower} = \frac{\pi}{4}\left(\left(D_{tower} + T_t + 0.001\ H_{tower} \times 2\right)^2 - \left(D_{tower}{}^2\right)\right) H_{tower} CM_{tower} \quad (6)$$

$$C_{tg} = C_{tower}\ \ P_{tg} \quad (7)$$

$$C_e = \ a + b\ S^n \quad (8)$$

$$C_{inve} = (1 + P_{O\&M} + P_{ins})\ \left(\sum C_e + C_{tower} + C_{tg}\right) \quad (9)$$

where C_{tower}, C_{tg},C_e and C_{inve} represent the cost of tower, turbine generator, other equipment, and total investment respectively. D_{tower}, H_{tower} is the diameter

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Table 3. The economic parameter used and the estimated results of model DET.

Parameter	Unit	Value
Life time	year	30
CM_{tower}	\$/ m^3	179.15
P_{tg}	%	10
$P_{o\&M}$	%	0.5
P_{ins}	%	4
C_{tower}	M\$	597.6
C_{tg}	M\$	47.8
$\sum c_e$	M\$	3.6
C_{inve}	M\$	677.8

and the height of tower, T_t donates tower wall thickness, and it is presumed that average chimney thickness increases 1 mm per 1 m that chimney height is increased.[21] $CM_{tower}$is defined as the cost of specific material used in tower, which is ready-mixed concrete and at average of 137$ per cubic meter in 2022. C_{tg} assumed the P_{tg} percent of the cost of tower.[22] Cost of installment is assumed the 4% of total equipment cost.[23] The cost of pipe, pump and evaporator part use a generic cost related algebraic Eqn (8).[24] The summarized economic results are listed in Table 3.

The results agree well with the data in[20] research. The small difference lies in the fact that in this model, seawater is assumed to be a free resource and is not included in the cost estimation.

Taking into account that 43% of the generated power is used for pumping water and average electricity price is 0.09 kWh/$ in Jordan in2022, the annual revenue for this model is estimated to be approximately 68.4 M$. The corresponding internal rate of return is 14.7%.

The above economic estimates of DET at different scales and locations consistently illustrate that investing in DET as an energy production technology can obtain significant economic benefits.

Economic benefit from CH4 removal

In the EU ETS (Emissions Trading System), the price of CH_4 is usually expressed as the cost of one ton of CO_2 equivalent, or ton of CO_2e.

Through investing in DET, the annual profit from the sale of carbon credits can be estimated as follows:

Profit per year = Carbon price (€/tons) × currency rate (EUR/USD) × 311.4 tons × 365 days

Table 4. Potential profit of CH_4 removal at different locations.

Location	Duration of solar radiation (h)	Profit ($/million)
Jordan Desert	13	10.3
Sahara Desert	12	9.5
Atacama Desert	14	11.1
Death Valley	14	11.1
Arabian Desert	12	9.5
Australian Outback	10	7.9

The carbon price in the EU ETS varied from €5 to a maximum of €30 per ton of CO_2e by 2021. Based on the price of €90.22 on December 20, 2022, the estimated annual profit generated from a single DET would be $10.3 million (in addition to the profit for electricity selling, i.e., a 15% increase in profit thanks to CH_4 removal in addition to electricity generation).

In recent years, CO_2 prices in the EU ETS have generally shown an upward trend, Fig. 3. As countries pay attention to climate change, carbon prices could continue to rise.[25] It is foreseeable that the annual profit figure may far exceed $10.3 million.

If DETs can be implemented widely and they can achieve the same level of air output, and that the air humidity and gas content in the area where the equipment is located does not affect the performance of the DET, the potential profit of DETs in other desert areas can be calculated as shown in the below Table 4.

Given the limitations of the available data, this study aims to add to the existing literature by focusing on the additional benefit of the DET technology, specifically it can remove atmospheric CH_4 without adding additional equipment, materials or costs compared with other NETs.

Possible scale of DET deployment

According to the International Energy Agency's (IEA) latest projections, global energy demand is expected to increase by about 4.6% per year from 2019 to 2040.[26] New sources of green energy is in high demand. Building 1800 DETs can match 1% global electricity consumption of the world based on the consumption in 2020. In this case, the total amount of CH_4 removal by 1800 DETs can be up to 8.2 million tons CH_4 per year.

Therefore, while DETs may not be a complete solution to our energy needs, they offer a promising

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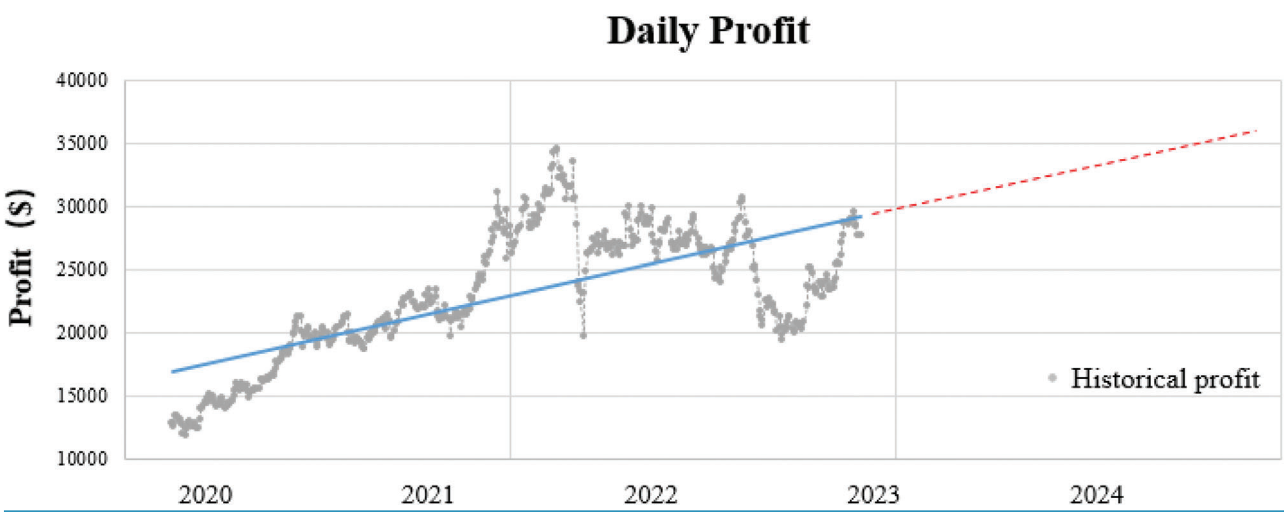

Figure 3. Daily profit and predicted profit from 2021 to 2024.

approach to sustainable power generation and environmental remediation to be included in the future energy portfolio. Future research should continue to explore the potential benefits and limitations of DET technology and identify suitable locations for their deployment to maximize their impact on reducing greenhouse gas emissions and other pollutants.

Further co-benefits of DET

Downdraft energy tower technology is a green power generation method that offers multiple benefits for the environment. In addition to its ability to remove CH_4 from the atmosphere, the enhanced °OH also reduces the levels of other pollutants such as volatile organic compounds (VOCs) and sulfur dioxide.[27] Other greenhouse gases, such as hydrofluorocarbons (HFCs) and hydrochlorofluorocarbons (HCFCs),[28] which have high global warming potentials (GWP), can also be removed by the DET. This makes DET an effective tool for generating sustainable power, reducing multiple greenhouse gases and air pollutants.[29]

Additional research and modeling is needed to fully evaluate the DET potential as a NET,[30] as in polluted regions where nitrogen oxides ($NOx = NO + NO_2$) are present, the amount of O_3 and °OH generated can be sensibly higher, and therefore the possible amount of CH_4 oxidized can be increased.

The DET also has the added benefit of enhancing the humidity locally and possibly producing rainfall at a distance when moist air is blown from the bottom of the tower. This can also help to increase water supply for native vegetation, promoting growth and allowing the plants to capture atmospheric CO_2 through photosynthesis for biological carbon sequestration.[31,32] During operation, the DET uses excess seawater to prevent salt fog,[8] which has a dense and cold composition that contains relatively high concentrations of CO_2. This is because CO_2 is more soluble in colder temperatures, and most of the air released by the DET is washed away by the water. If the cold brine is reintroduced into the ocean, the increased density causes it to sink to depths greater than 1,000 m. At these depths, the CO_2 is effectively stored for centuries because of the thermohaline circulation.[33]

Richer countries historically responsible for high emissions can provide financial compensation to poorer countries disproportionately affected by climate change, under an agreement from the 27th United Nations Climate Change Conference (COP27) to establish a loss and damage fund.[34] Perhaps wealthy countries can support investment in the construction of DET in these countries, and taking the economic benefits of CH_4 removal as economic compensation is also a direction worthy of research.

Conclusions

The Det technology not only is a promising renewable energy technology but also can provide multiple co-benefits for the environment. One of the major co-benefits could be its ability for reducing atmospheric CH_4, which is achieved without adding additional equipment, materials or costs compared to other negative emission technologies. In multiple case studies, the CH_4 removal offers at least 15% increase in profit in addition to electricity generation.

It is hoped that this work could inspire more detailed studies (e.g., process modeling, life cycle analysis and techno economic analysis) from researchers in the wider community. Ultimately, together, we can design and implement this technology as one of the tools to reduce greenhouse gases at large scale.

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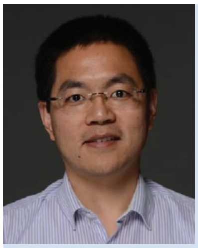

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