Direct cooling of the atmosphere by heat transfer

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ABSTRACT
Global warming is currently one of the greatest challenges to humanity. So far, the attempts to mitigate global warming have been based exclusively on the reduction of carbon dioxide concentration in the atmosphere. The main methods include reduction of CO_2 emissions and the removal of carbon dioxide from the atmosphere, as in the case of carbon capture and storage. One of the problems with this approach is that the lifetime of CO_2 in the atmosphere is very long and the effect of the CO_2 emission reduction on atmospheric temperature decrease will only become meaningful after a number of decades. In this work I am proposing to reduce the global atmospheric temperature increase, or even to decrease the temperature by removing sensible heat from the atmosphere and transferring it to media outside the atmosphere such as water or land mass. One of the main advantages of atmospheric heat removal is that unlike CO_2 emission reduction, it has an immediate effect on atmospheric temperature. Also, the technology is simple, inexpensive and relatively well developed. Four different methods to achieve that are proposed: one by direct heat exchange between the atmosphere and cooling water, and the other three based on the process of isothermal gas compression and expansion. The latter three methods combine the cooling of the atmosphere with other practically important features: energy storage, energy transport and power generation. Proven patented technical solutions to achieve the atmospheric cooling are shown. The energy balance and the financial and materials requirements to build the needed equipment show that the complete stop of global warming is achievable in a period of several years. It should be noted that the proposed solution to global warming is temporary and will work only for several decades. In the longer term, CO_2 emission decrease (which needs to start as soon as possible) should take over as the main method of global warming mitigation.

INTRODUCTION

The process of chemical fuel oxidation involves two significant types of emissions to the environment: *mass* (primarily carbon dioxide and water vapor) and *energy* (sensible heat and some electromagnetic energy in the infrared and visible spectrum)[1].

Human activities have been contributing to the increase in atmospheric temperature over the past 150 years [2]. So far, the attempts to mitigate global warming have been based exclusively on the reduction of CO_2 concentrations in the atmosphere[3]. One of the problems with this approach is that the lifetime of CO_2 in the atmosphere is very long, in the order of centuries and even longer[4]. Therefore, the effect of the CO_2 emission reduction on atmospheric temperature decrease will only become meaningful after a number of decades.

Here I am proposing to mitigate global warming by removing sensible heat from the atmosphere (i.e., via direct cooling of the atmosphere)[5]. The heat removed from the atmosphere is transferred to another medium, such as water or land mass. In this scenario the atmosphere is a heat source, and the water or land are heat sinks in a thermodynamic cycle. In this work, the word "heat" is used as a synonym to "sensible heat" unless indicated otherwise.

One of the main advantages of atmospheric heat removal is that unlike CO_2 emission reduction, it has an immediate effect on atmospheric temperature. Also, the technology, as seen below, is simple, inexpensive and relatively well developed. Four main ways to transfer heat from the atmosphere to water or land are proposed in this work: (1) by direct heat transfer (2) in combination with isothermal compressed air energy storage (ItCAES); (3) in combination with energy transport and storage; (4) in combination with electric power generation. Cases (2-4) are based on isothermal compression and expansion of air. It is well known that when an ideal gas is compressed (i.e., its volume is decreased and pressure is increased), this process generates heat energy, while when gas is expanded (i.e., its volume is increased and pressure is decreased), heat energy is consumed[6]. In an ideal isothermal process, the heat energy generated during compression (Q_{compr}) is equal to the mechanical energy used for compressing the gas (E_{compr}). The heat energy consumed by the expanding gas (Q_{exp}) is equal to the mechanical energy generated (E_{exp}). When a certain amount of gas is first isothermally compressed and then isothermally expanded at the same temperature, then $Q_{exp} = Q_{compr} = E_{exp} = E_{compr}$. Atmospheric air can be considered an ideal gas. Since true isothermal process is not achievable in real life, the term "isothermal" will be used in this work to describe not only the ideal process but also near-isothermal real conditions.

CONCEPTUAL OVERVIEW

Atmospheric cooling by heat exchange

The simplest way to transfer heat is by exchanging it directly between the atmosphere and colder water or land (Fig. 1a). The main condition here is that the temperature of the atmosphere is above that of the heat sink. Since in general, atmospheric air is located away from the cooling water or land, it is necessary to transport either air or water/coolant fluid to the heat exchanger (Fig. 2).

The cooling medium can be ocean water. It is well known that at most locations, the ocean temperature decreases as the depth increases, reaching approximately 6°C at 500 m and 4°C at 1000 m and below[7]. In general, the average near-surface air temperature between the latitudes of 45°N to 45°S[8] is generally higher than the ocean temperature deep below the surface, which satisfies the main condition for this method.

Atmospheric heat can also be transferred to groundwater or land. The temperature of groundwater at depths greater than 3 meters below the surface tends to be close to the year-round average temperature of the atmosphere at the same location[9][10]. Since direct cooling of the atmosphere is achieved when air temperature is higher than water or land temperature, this condition can be met only during certain seasons and times of day, mostly during daytime in the summer.

Atmospheric cooling combined with energy storage

As mentioned above, heat is generated during gas compression and is consumed by the gas during expansion. As shown in Fig. 1b, air is compressed isothermally using mechanical energy, and subsequently stored in a vessel. The heat generated during compression is transferred to water or land mass via heat exchange. The compressed air is then expanded isothermally to ambient pressure, generating mechanical energy, and the spent air is released into the atmosphere. The heat consumed by the expanding air is drawn from the atmosphere via heat exchange. The process of compression (which consumes mechanical/electrical energy) can be carried out at different times than the process of expansion (which generates mechanical/electrical energy). Therefore, compressed air vessel can be used for energy storage. By definition, energy storage is based on the consumption of electrical energy, produced at one time for use at a later time in order to reduce imbalance between electricity demand and generation[11]. It has been dubbed "the Holy Grail" of renewable energy[12] because of the need to smooth the highly variable wind and solar power generation. When there is a peak in wind or solar power generation, the excess electricity produced will run the isothermal compressor in Fig. 1b, thus mitigating the peak. On the other hand, when there is a "valley" in electricity generation (characterized by insufficient wind or sun), the previously compressed air will be isothermally expanded to generate electricity and fill the valley, thus creating a time profile for electricity generation fitting the demand profile. Therefore, the system shown in Fig. 1b can be used simultaneously for energy storage and atmospheric cooling.

When atmospheric cooling is combined with energy storage, the temperature of the atmosphere (heat source) can be higher, lower or equal to the temperature of the heat sink. Isothermal compression and expansion are described by the following equation[13]:

$$Q = E_{mech} = nRT\ln(p_{final}/p_{in}) \quad (1)$$

where Q is the amount of heat exchanged with the surroundings, E_{mech} is the amount of mechanical energy used or generated, n is the number of moles of gas, R is the universal gas constant, T is the absolute temperature, p_{in} is the initial gas pressure and p_{final} is the final gas pressure. When the temperature of isothermal compression (T_{compr}) is lower than the temperature of isothermal expansion (T_{exp}), there is a net mechanical energy gain, as the amount of mechanical energy generated by the system ($E_{mech, out}$) is higher than the mechanical energy supplied ($E_{mech, in}$):

$$-Q_{out} = E_{mech, in} = nRT_{compr}\ln(p_{final,compr}/p_o) \quad (2)$$

$$Q_{in} = -E_{mech, out} = nRT_{exp}\ln(p_{in,exp}/p_o) \quad (3)$$

where p_o is atmospheric pressure, assumed to remain constant between compression input and expansion output and the subscripts *compr* and *exp* stand for compression and expansion, respectively. Once the isothermal compression at low temperature is complete, isochoric compression takes place due to the compressed air being heated from T_{compr} to T_{exp}. The air pressure at the end of the isochoric process ($p_{in,exp}$), which precedes isothermal expansion, can be calculated using the ideal gas law as:

$$p_{in,exp} = p_{final,compr} T_{exp} / T_{compr} \tag{4}$$

Therefore, the thermodynamic efficiency of the proposed system is:

$$\eta = \frac{E_{mech,out} - E_{mech,in}}{Q_{in}} = 1 - \frac{T_{compr} ln \frac{p_{final,compr}}{p_{atm}}}{T_{exp} ln \frac{p_{final,compr} T_{exp}}{p_{atm} T_{compr}}} \tag{5}$$

Thus, when the expansion temperature is higher than that of compression, under ideal conditions the entire ItCAES system will not only act as an energy storage system, but also as a net generator of mechanical energy. For example, when 1 MW of electricity is stored at a temperature difference of 20°C and a pressure of 100 atm, the system as a whole will generate 81 kW of mechanical/electric energy (Eq. 5). This, of course, is the case when there are no energy losses in the system. Incidentally, ItC and ItE described below have very low energy losses.

The opposite is also true; when the expansion temperature happens to be lower than the compression temperature, the ItCAES will lose mechanical energy, i.e. $\eta<0$, according to Eq. 5, but heat will still flow from air to the heat sink.

Atmospheric cooling combined with energy transport

Figure 1c illustrates the case where the compressed air storage tank has a cylindrical shape, with a diameter significantly smaller than the length, forming a pipe. In this scenario, the compressed air tank can be used not only for storage of compressed air, but also for energy transport by facilitating the movement of compressed air from the input of the cylindrical pipe toward its exit. In the case of energy transport, heat management of the ItC and ItE is performed the same way as in the case of energy storage above.

When atmospheric cooling is combined with energy transport, the temperature of the atmosphere (heat source) does not need to be higher than the temperature of the heat sink. However, the greater the temperature difference between the heat source (atmosphere) and the heat sink (water or land), the greater the round-trip efficiency of the process of energy transport, as shown in Eq. 5. Our preliminary data indicates that both the capital cost and the energy losses incurred by energy transport using compressed air will be comparable to those in the current form of energy transport facilitated by high voltage electricity transmission lines.

Atmospheric cooling combined with electric power generation

It is well known that the temperature difference between physical objects can be used to transform heat energy into mechanical energy, and subsequently into electricity, as shown by Eq. 5. This is the basic principle on which thermal power plants operate. In conventional thermal power plants, the higher temperature is the direct result of fuel burning, while the lower temperature is that of the environment (usually air or water). Therefore, heat flows from the heated object (usually a fluid) to the ambient atmosphere or water. However, there is also a process, where the higher temperature is that of the environment (usually surface water), while the lower temperature is that of deep ocean water[14]. This process was first proposed at the end of the 19th century[15], in order to leverage the difference between ocean temperatures at different depths for the generation of mechanical and electric energy. In this scenario heat flows from the surface water to the depths of the ocean. In tropical latitudes where the temperature difference between the surface of the ocean and depths below 500 m is approximately 25°C, therefore using Eq. 5, the ideal efficiency is 10%. So far, primarily vapor-based technologies such as the organic Rankine cycle have been proposed and tested on sea water for power generation. Actual efficiencies of only 2-3% have been reported, mostly due to the energy losses of vapor cycles[16].

In this work, the generation of mechanical/electrical energy is accomplished by using a scheme similar to that in cases of energy storage and transport above. The main difference here is that the temperature of the heat sink (ocean or other water) must always be lower than the temperature of the heat source (atmosphere) in order to generate mechanical/electrical energy. The schematic of the process is shown in Fig. 1d.

CAPACITY OF HEAT SINKS

When a certain amount of heat Q is transferred from or to a physical object having a mass m, the change in temperature ΔT is[17]:

$$\Delta T = \frac{Q}{mC_p} \tag{6}$$

where C_p is the specific heat capacity. Eq. 6 can be used to estimate the rise in heat sink temperature due to cooling of the atmosphere. The coefficient of proportionality between the amount of heat exchanged and the temperature change is (mC_p), which represents the overall heat capacity. Since the total mass of the atmosphere is $5.15 \cdot 10^{18}$ kg and C_p is 1005 J/kgK, then $(mC_p)_{atm} = 5.2 \cdot 10^{21}$ J/K. The cooling of the atmosphere in any of the cases 1-4 above can be achieved by transferring heat to heat sinks such as oceans, seas, rivers, lake water, groundwater or land mass. The temperature increase of the Earth's atmosphere since 1981 has been close to linear at approximately ΔT_{atm}=0.018°C per year[18]. Therefore, the amount of heat to be added annually to heat sinks to stop global warming (to flatten the temperature growth curve) is $Q_{stop\ global\ warming} = \Delta T_{atm}(mC_p)_{atm} = 0.018 \cdot 5.2 \cdot 10^{21} = 0.94 \cdot 10^{20}$ J.

Cooling with fresh water

Thermal power plants (largely powered by coal, natural gas and nuclear fission) have an average efficiency of 34%[19]. This means that the generation of 1 GW of electricity will result in the release of 1.9 GW waste heat which is expelled to the surroundings (water or atmosphere). Here we are not considering direct and indirect air cooling of power plants, as we are interested only in heat rejection to water. Global water withdrawal for power plant cooling in 2015 was 500 km^3 of which 290 km^3 was freshwater [20]. The temperature increase of water used for the cooling of power plants is currently not considered a climate change factor. Worldwide, 37% of the thermal capacity of thermal power plants is cooled by once-through cooling systems using fresh or salt water[21]. Since the world generates $2.73 \cdot 10^{13}$ kWh[22] or $0.98 \cdot 10^{20}$ J of electricity annually, the heat released to cooling water at 34% average plant efficiency is $0.69 \cdot 10^{20}$ J. Therefore, if all the water-cooled power plants are replaced by renewable electricity generation equipped with energy storage (assuming 24h/day storage), the heat load on cooling water worldwide will increase by only 36%, and the global warming will be eliminated.

Cooling with ocean water

The overall heat capacity of the oceans is $(mC_p)_{ocean}=5.4 \cdot 10^{24}$ J/K, as $m=1.4 \cdot 10^{21}$ kg and $C_p=3850$ J/kgK. The temperature increase of the Earth's atmosphere is approximately $\Delta T_{atm}=0.018$°C per year. Therefore, in order to stop the process of global warming (i.e., to flatten the air temperature vs. time curve), assuming a well-mixed atmosphere[23], $\Delta T_{ocean} = \Delta T_{atm}(mC_p)_{atm}/(mC_p)_{ocean} = 1.7 \cdot 10^{-5}$ °K, i.e., the ocean water will warm up by only 0.000017°C annually, given that all the heat drawn from the atmosphere is equally distributed throughout the entire planetary ocean mass. However, it is more probable that the heat drawn from the atmosphere to the ocean will remain for a relatively long time mostly in depths between 0 and 2000 m. It has been shown that the average annual addition of heat to the world ocean due to global warming in years 2005-2018 at 0-2000 m depth is $1.5 \cdot 10^{22}$ J[24]. As shown above, the amount of heat to be added annually to the ocean to stop global warming is $0.94 \cdot 10^{20}$ J, therefore it would add only 0.6% to the current ocean heating rate.

Cooling by groundwater or land

One of the challenges of constructing a renewable power generation facility featuring atmospheric cooling is finding a heat sink when the system is located at a significant distance from fresh- or sea-water bodies. In these situations, cooling may be performed by using groundwater or underground land. When used for atmospheric cooling, the heating of land is impossible to estimate due to its large mass and uneven heat distribution.

Cooling of the atmosphere by replacing coal power plants with renewable power generation systems combined with energy storage and transport

Currently the worldwide coal power plant capacity is 2 200 GW[25], or $0.69*10^{20}$ J of electricity annually. As calculated above, the amount of heat that needs to be removed from the atmosphere in order to stop global warming is $0.94 \cdot 10^{20}$ J. Therefore, by replacing all coal power plants with renewable power generation systems, combined with compressed air energy storage that aids atmospheric cooling as described above, the increase of atmospheric temperature rise (global warming) will be reduced by 73%. The installed energy storage mechanisms are assumed to provide 24 h/day storage. These calculations do not take into account the elimination of CO_2 and heat emissions by retiring traditional coal power plants, which will additionally reduce atmospheric temperature increase.

Cooling of the atmosphere by boosting the functionality of existing and future wind and solar generation facilities using ItCAES

The cumulative power generated by solar and wind systems in 2026 is expected to be 5 500 TWh[26]. If combined with ItCAES, this translates to $2.0 \cdot 10^{19}$ J of heat being removed from the atmosphere annually at 24 hours per day storage. The profile of atmospheric temperature change associated with the atmospheric cooling by the installed solar and wind power stations is shown in Fig. 3a.

TECHNICAL SOLUTION FOR ISOTHERMAL COMPRESSION/EXPANSION

In order to commercialize systems shown in Figs. 1b-1d, it is imperative to use a compressor and expander operating at near-isothermal conditions. Until recently, there had been no known commercial isothermal compressors or expanders[27]. The main reason for this is the lack of efficient heat transfer between the compressing or the expanding gas and the surroundings. Recently an invention was patented for isothermal compressed air energy storage[28]. The invention is based on a unique type of isothermal compressor/expander, having a very high heat transfer rate between the compressing/expanding gas and the surroundings, and therefore, very high isothermal energy efficiency. The system can be used as a combination of compressor and expander (ItC/E), or individually only as a compressor (ItC) or an expander (ItE).

The process of air compression by ItC is shown in Figs. 3a and 3b. During air compression, mechanical energy is added to the ItC by an electric motor (Fig. 3b). Isothermal air compression consists of two phases. In the first phase (shown in Fig. 3a), fresh air is drawn from the atmosphere. A hydraulic piston moves to the left, which results in hydraulic fluid being withdrawn from the C/E vessel. This leads to an increase in air volume. Check valve 1 opens and allows fresh air to be drawn from the atmosphere into the air chamber of the C/E vessel. Figure 3b shows the second phase of air compression. Here the hydraulic piston moves from left to right, as indicated by the arrow. Hydraulic fluid fills the liquid chamber of the C/E vessel, which results in a decrease of the air chamber volume i.e., air compression. Therefore, pressure in the air chamber increases. The process of air compression produces heat, which is transferred from the compressing air to the surroundings via heat transfer across the compression vessel wall (shown with an arrow in Fig. 3b). The compressed air enters the compressed air vessel. The compression process continues by cycling through the first phase followed by the second phase again.

Air expansion by ItE is shown schematically in Figs. 3c and 3d. During expansion, mechanical energy is generated and transferred to an electric generator (Fig. 3c). Valves 3 and 4 are controllable solenoid valves. Isothermal air expansion consists of two phases. In the first phase (shown in Fig. 3c), compressed air is transferred from the compressed air vessel to the air chamber of the C/E vessel by opening valve 3 for a certain period of time. The duration of opening this valve is determined in such a way, so as to ensure that at the end of this phase (when the hydraulic piston is at its far-left position) the pressure of expanding air is close to the ambient air pressure. During the first phase of gas expansion, heat is consumed by the expanding air. In order to keep the expanding air temperature constant, heat is transferred from the surroundings to the air compartment in the C/E vessel (shown by an arrow in Fig. 3c). Figure 3d shows the second phase of air expansion. Here the hydraulic piston moves from left to right, as shown by the arrow. Hydraulic fluid fills the liquid chamber of the C/E vessel, which results in a decrease of the air chamber volume. Solenoid valve 4 is opened during this phase. As a result, spent air is released to the surroundings (atmosphere) at near-atmospheric pressure. The expansion process continues by cycling through the first phase followed by the second phase.

Heat transfer between compressing/expanding gas and its surroundings

Internal heat transfer. The primary bottleneck in both compression and expansion is the convective heat transfer between the compressing or expanding air and the inner wall of the compression/expansion vessel. The air-wall heat transfer coefficient inside of the compression/expansion vessel was found to be in the range 120 to 210 W/m^2K. In order to increase these values, an extended heat transfer surface can be installed inside of the compression vessel. Since the air volume in the compression vessel at the end of the compression process must be minimized in order to avoid dead zones, the extended heat transfer elements can be comprised of either solid or perforated metal sheets or films.

External heat transfer. In the processes of compression and expansion, the other bottleneck is the mostly convective heat transfer between the outer wall of the expansion vessel and the surroundings (typically comprising atmospheric air). Therefore, extended heat transfer elements[29] may also be needed on the outside of the expansion vessel. Alternatively, an external heat exchanger similar to an automobile radiator may be used. During compression, the surroundings (the heat sink) usually consist of cooling water. The heat transfer coefficient between the outer wall of the compression unit and the cooling water is is much higher than the internal heat transfer coefficient specified above[30]. Therefore, the external compression vessel wall does not require extended heat transfer elements. In most cases the cooling water can flow inside a cooling jacket, surrounding the compression vessel.

Fig. 6 shows the temperature change observed during 90 minutes of compression in the one-stage unit. The temperature of the compressed air leaving the ItC did not change significantly during that time, and also between the compressed gas and the surrounding air. This result shows that the ItC/E is close to an ideal isothermal device.

It should be noted that even if the heat transfer rate between the expanding air and the atmosphere is not sufficient to maintain isothermal conditions, i.e., the fully expanded air has a temperature lower than that of the surrounding atmosphere, the cold expanded gas leaving the expansion vessel will still cool the atmosphere by mixing with it. In this case the expansion will be adiabatic. Consequently, the roundtrip energy efficiency of the compressed air energy storage process will be somewhat lower than in the case of purely isothermal compression and expansion. Therefore, there is a tradeoff between the cost of using an air heat exchanger and the energy efficiency of the process.

MATERIALS AND COST REQUIREMENTS

To build ItCAES with an atmospheric cooling system described above, able to decrease the atmospheric temperature by 0.018°C annually, i.e., to completely stop global warming, the total world-wide capital cost is estimated at $150 billion. The capital expense associated with building compressed air energy storage will translate to a cost increase of less than 1 cent/kWh for renewable electricity. In fact, energy storage is an essential component of wind and solar power generation due to the intrinsic variability of these natural energy sources[31]. Currently, many of the new wind and solar generation facilities are equipped with Li-ion battery storage[32] having an average capital cost of 15 cents/kWh[33], i.e., almost an order of magnitude higher than that of the proposed ItCAES. In addition, Li-ion batteries have approximately 85% efficiency[34] which means that 15% of the stored energy ends up heating the atmosphere. It seems that battery energy storage will be most appropriate for small to intermediate storage capacities, below approx. 300 MWh[34]. Therefore, building an atmospheric cooling system combined with energy storage will not only decrease the atmospheric temperature, but will also significantly reduce the current capital cost of wind and solar power generation equipped with energy storage.

The amount of steel required to build an ItCAES system designed to eliminate global warming is estimated at 50 million metric tons. As a comparison, the current annual worldwide steel production is close to 2 billion tons. The amount of copper needed for the electric motor/generator is 3 million tons, while world copper production is 22 million tons per year. Since it is anticipated that construction of the atmosphere-cooling ItCAES will take several years, up to a decade, the strain on the production of iron and copper will be minimal. The material requirements for the heat exchangers are not included in these calculations.

REDUCTION OF COOLING EFFECT IN THE ATMOSPHERE

There is a possibility that some of the cold air released by the systems described above may be reheated by land or water, thus reducing the cooling effect on the atmosphere. Since colder air has higher density than warmer air, it will tend to move downwards, especially when the weather is calm. As a result, sensible or latent heat may be transferred from the surface of land or water to the atmosphere. Another possible factor in the reduction of the cooling effect of the proposed technologies is the decrease of IR cooling or air at lower air temperatures. Furthermore, local lowering of atmospheric temperature can result in an increase in precipitation, leading to transfer of heat from liquid water to the atmosphere. These negative effects can be mitigated by increasing the volumetric flow rate of cooled air which will lead to a reduction of the temperature difference between the cooled air and the surrounding atmosphere. In addition, increase in precipitation can be reduced by placing the atmospheric cooling systems in dryer air locations such as deserts.

CONCLUSIONS

A set of technologies for combating global warming of the atmosphere is proposed here. The main idea is to remove sensible heat directly from the atmosphere and transfer it to other media such as water (fresh or ocean) or land. The heat balance shows that the temperature increase of water will be minimal even when global warming is brought to a complete halt. The process of cooling of the atmosphere can be combined with other useful processes such as energy storage, energy transport and electricity generation. The associated cost, material balance, resource availability and technological readiness indicate that the atmospheric cooling technologies proposed here are viable in the short term. In order to stop global warming of the atmosphere, i.e., to flatten the temperature rise curve, approximately $150 Billion will be required to build 10,000 ItC/E units worldwide, 300 MW each. However, in order to avoid excessive heating of the oceans, this method should not be used for periods exceeding several decades. In the longer term, CO_2 emission decrease (which needs to start as soon as possible) should take over as the main method of global warming mitigation.

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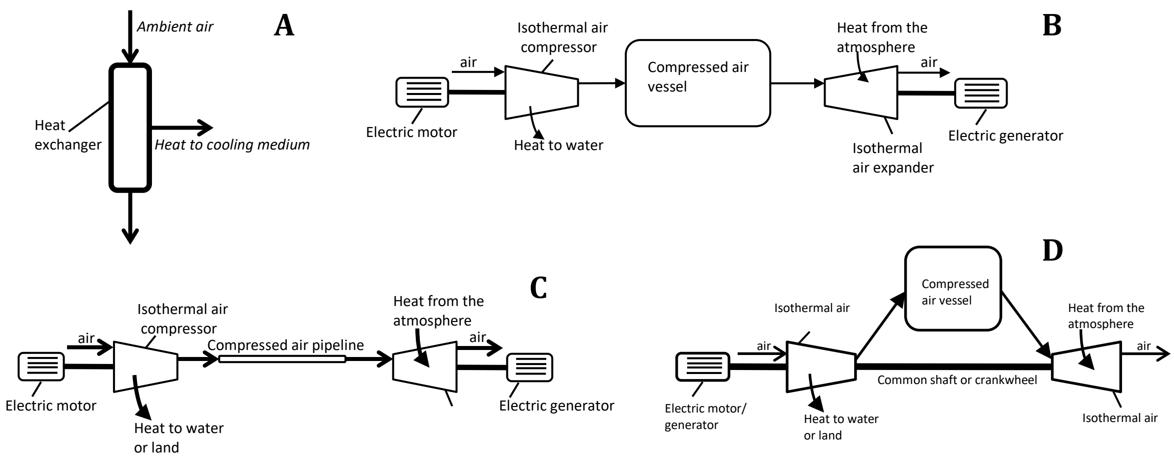

Fig. 1. Schematics of the four technologies to remove heat from the atmosphere.

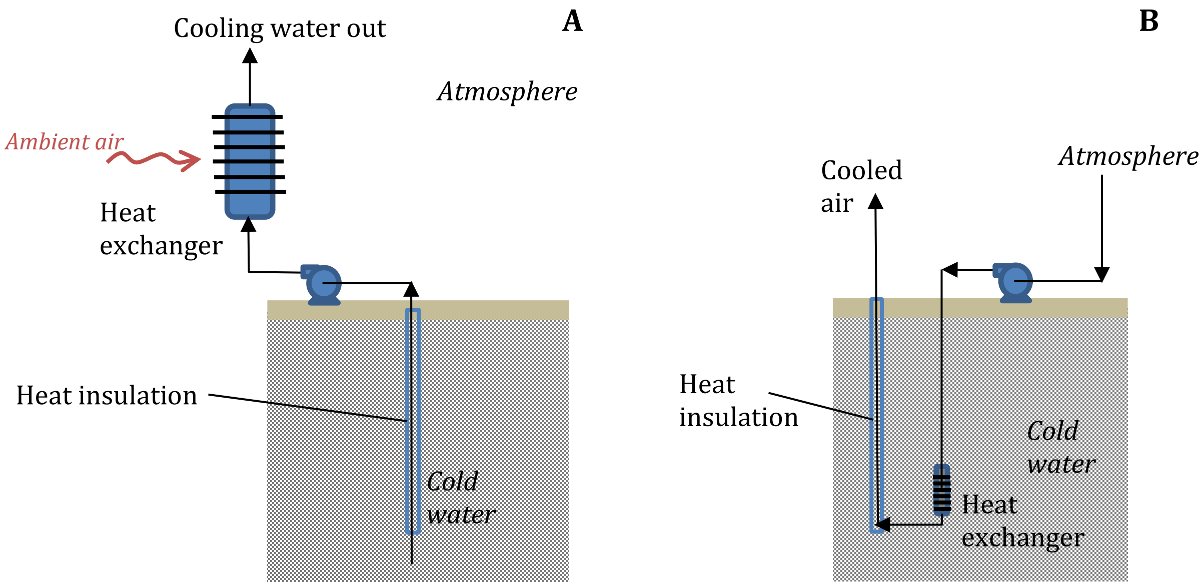

Fig. 2. Direct heat exchange between the atmosphere and cooling water. A: heat exchanger in the air; B: heat exchanger in cooling water.

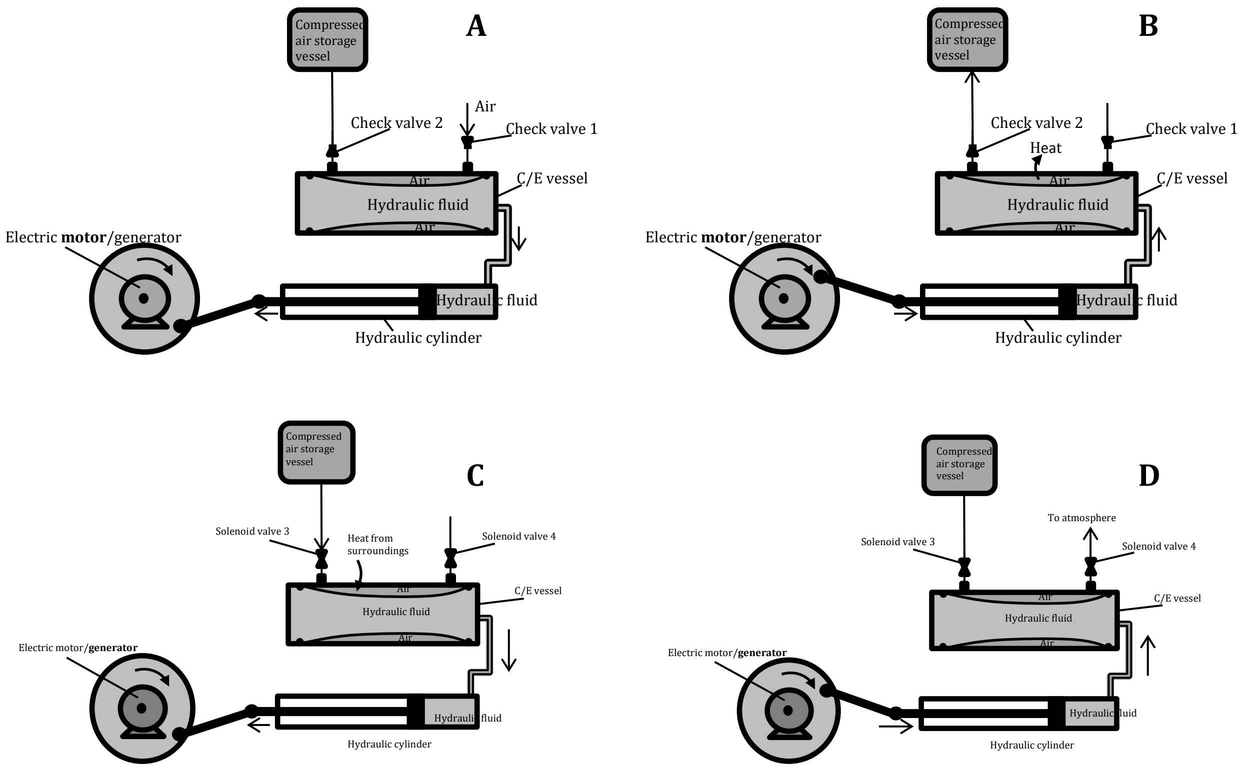

Fig. 3. Schematics of the ItCAES. A: first cycle of compression; B: second cycle of compression; C: first cycle of expansion; D: second cycle of expansion.

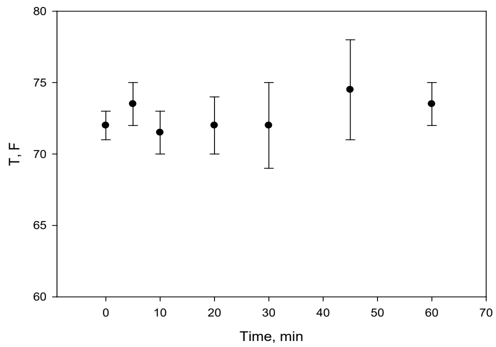

Fig. 4. Temperature change of compressed air during the process of compression.

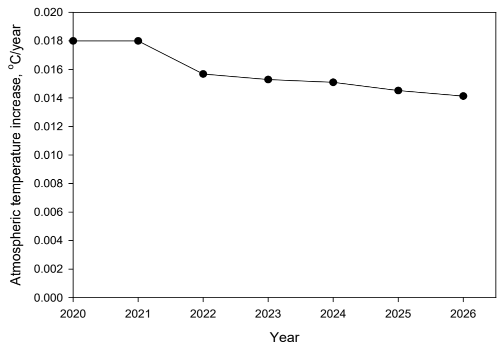

Fig. 5. Annual atmospheric temperature increase when ItCAES is used for energy storage in all wind and solar power generation.

SUPPLEMENTAL MATERIAL

Pilot-scale ItCAES

Two prototypes for testing the ItCAES were built: a one-stage, and a two-stage compression/expansion. In both cases the electric motor and generator were combined in one single reversible unit. Therefore, each of the two systems was perfectly reversible, acting as both compressor and expander, able to consume and generate electricity, respectively.

All the hydraulic cylinders in both prototypes were double-acting. The first prototype contained two two-stage compressor/expander units. The schematics of each two-stage unit is shown schematically in Fig. S1. The variable speed electric gearmotor/generator had a maximum power of 20 HP (K107 DRE180L4/TF, SEW Eurodrive, Bruchsal, Germany) and was controlled by MC07B0220-503-4-00/FSC11B (SEW Eurodrive, Bruchsal, Germany). The first stage hydraulic cylinders had a bore of 20 cm and a stroke of 50 cm (Parker Hannifin, Cleveland, OH, USA). The first stage compression/expansion vessels were steel cylinders having an inner diameter of 20 cm and a length of 1.14 m. The second stage hydraulic cylinders had a bore of 5 cm and a stroke of 50 cm (Parker Hannifin, Cleveland, OH, USA). They were connected to C/E vessels having an inner diameter of 5 cm and a length of 1.14 m. Both first- and second-stage C/E vessels had inside a nitrile rubber sleeve, fitting the inner diameter of the vessel. The rubber sleeves separated the hydraulic fluid at the inside from the compressing/expanding air at the outside of the sleeve (Fig. 3 in the main text). One layer of a stainless steel mesh with openings of 0.04 mm and wire diameter of 0.03 mm (McMaster-Carr, Elmhurst, IL, USA) placed between the rubber sleeve and the inner vessel wall was used as an extended heat transfer element inside each C/E vessel. No extended heat transfer elements were used outside of the C/E vessels. A photograph of the system is shown in Fig. S2.

The second ItCAES prototype was a single-stage compressor/expander system, shown schematically in Figs. S3 and S4. The variable speed electric gearmotor/generator was DRN132M4/FG/TF FLG MNTD, SEW Eurodrive, Bruchsal, Germany) with controller MC07B0220-503-4-00/FSC11B (SEW Eurodrive, Bruchsal, Germany). The system contained 7 double-acting hydraulic cylinders with a bore of 8.12 cm and a stroke of 50 cm, equipped with low-friction PTFE seals (Parker Hannifin, Cleveland, OH, USA). Each side of the hydraulic cylinders was connected to a custom-made steel compression/expansion vessel (14 in total) having an ID of 10.8 cm cm and a length of 1.02 m. The internals of the C/E vessels were the same as described above. A photograph of the unit is shown in Fig. S5.

The compressed air storage vessels were 11 K-size industrial high-pressure cylinders (49 L geometrical volume each) connected together.

Experimental

One of the most important parameters in this study is the isothermal efficiency, calculated using Eq. 5. Fig. 4 in the main text shows the change of the compressed air temperature in time at the exit of the compression vessels (the average of all 14) in the one-stage ItC/E. These results were obtained at an intake air flow rate of 6.2 L/s (STP) and a final pressure of 33 bar in the one-stage compression system.

Temperature difference between the compressing air and the surroundings was also measured in the two-stage ItC/E. When compressing 6.4 L/s air to 145 bar, the temperature of the compressed air leaving the first stage C/E vessel was less than 1°C above that of the ambient air, while the maximum temperature in the air leaving the second stage was between 3 and 4°C above the ambient, corresponding to 99% isothermal efficiency.

In the future commercial units, it is expected that the largest energy loss in the entire ItC/E system will be in the electric motor/generator which can be as low as 4%. The losses due to the mechanical energy transmission between the motor/generator and the C/E vessel are expected to be below 2%. The lowest losses in the system are expected to be in the process of compression and expansion, as reported above. Therefore, the overall energy efficiency of the entire compressor or expander is expected to be around 92%, and therefore, in the process of compression/expansion the roundtrip efficiency is expected to be above 85%.

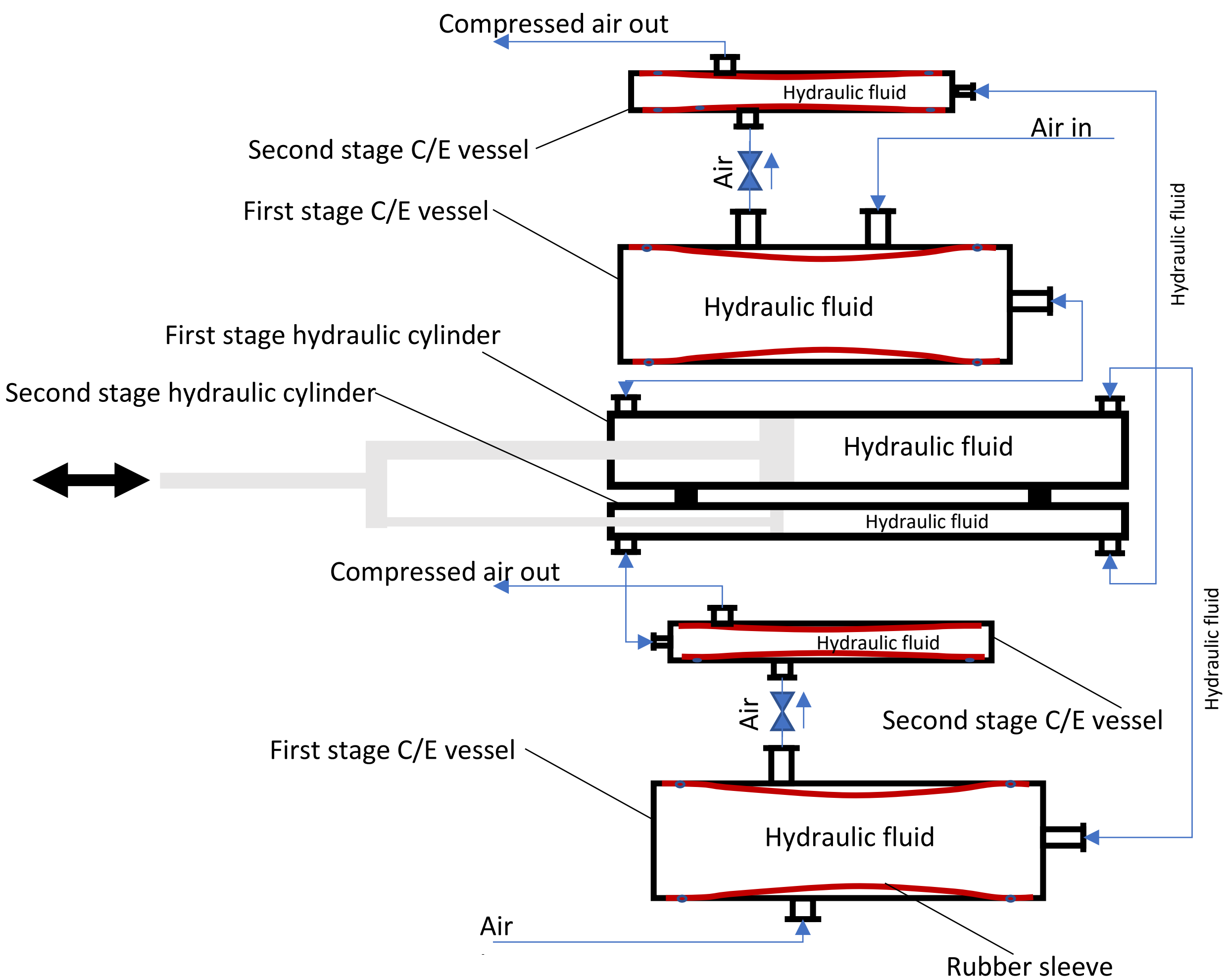

Fig. S1. Schematics of the two-stage compressor/expander.

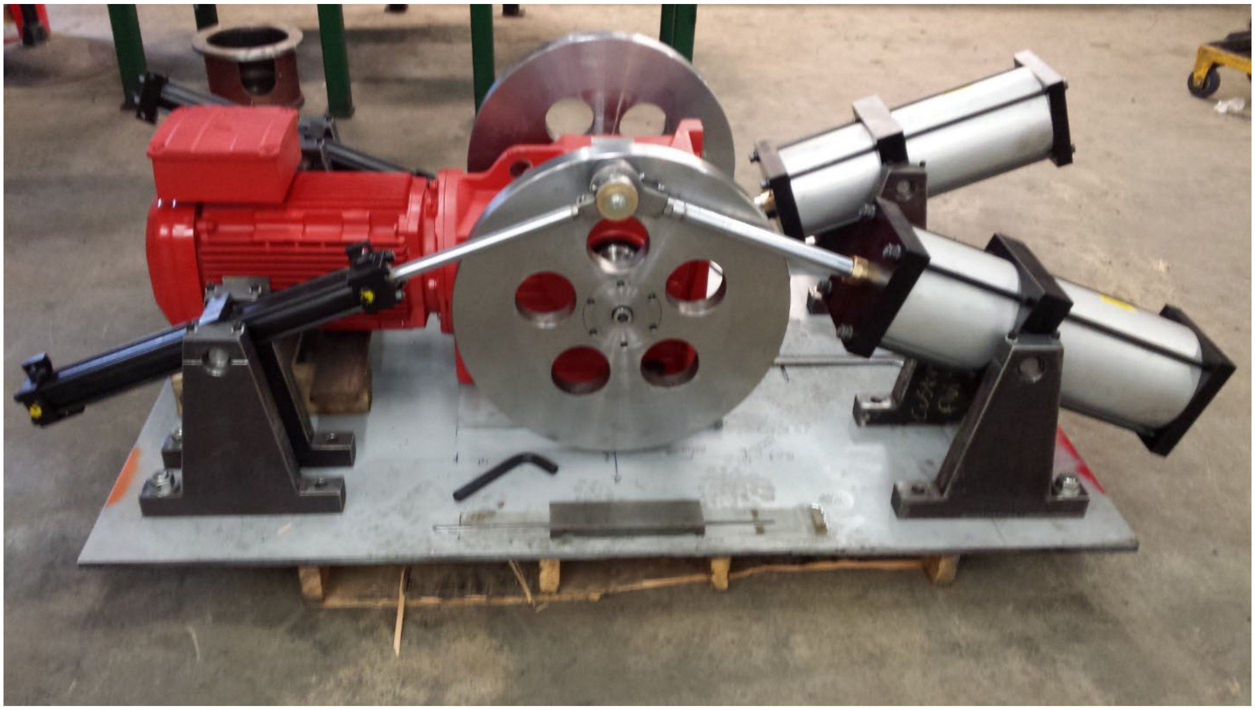

Fig. S2. Photograph of the two-stage compressor/expander (C/E vessels not attached).

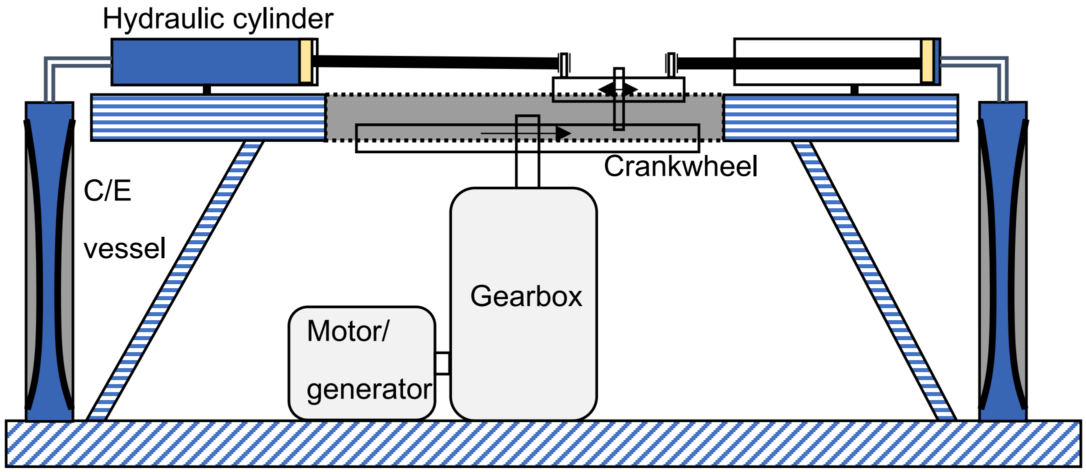

Fig. S3. Side view schematics of the one-stage compressor/expander. Only two out of seven hydraulic cylinders are shown.

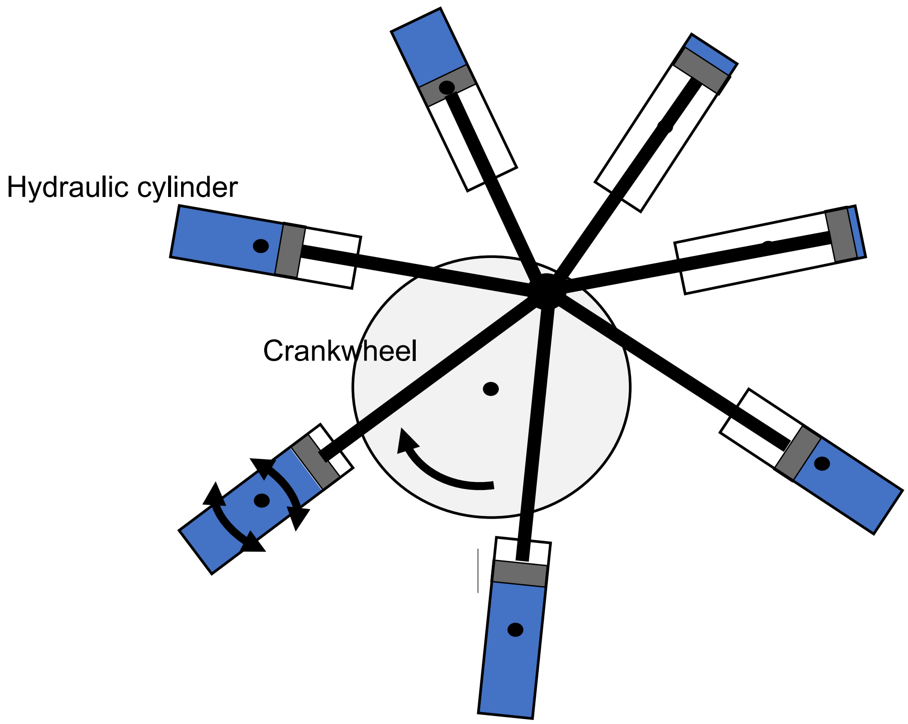

Fig. S4. Top-view schematics of the one-stage compressor/expander (C/E vessels not shown).

Fig. S5. Photograph of the one-stage compressor/expander.