

SYSTEMS AND METHODS FOR COMBINED CARBON CAPTURE AND THERMAL ENERGY STORAGE

TECHNICAL FIELD

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The present disclosure relates to systems and methods for combined carbon capture and thermal energy storage. In particular, the present disclosure relates to systems and methods for cold carbon capture and thermal energy transfer and storage.

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BACKGROUND

Carbon capture (CC) is among the most vital technologies under development to reduce CO₂ emissions. Various carbon capture technologies are available, such as chemical absorption, physical separation, oxy-fuel separation, membrane separation, calcium looping, chemical looping, direct separation, and supercritical CO₂ power cycles. Among them, chemical absorption is one of the most mature and widely used technologies.

Fig. 1A illustrates how a typical chemical absorption CC process operates: CO₂ is captured at a lower temperature and released or regenerated at a higher temperature, in this example absorption may be at a temperature of around 40°C, and desorption may be at a temperature of around 120°C. However, the high energy penalty is the main reason for reluctant market adoption, especially for direct air capture (DAC) – directly capturing low-concentration CO₂ from the ambient air (around 440 ppm CO₂).

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By neutralizing and offsetting historic and hard-to-mitigate emissions, DAC should remove 85 Mt of CO₂ in 2030 and 980 Mt in 2050 according to the Net Zero Emissions by 2050 Scenario of the International Energy Agency (IEA), requiring a significant scaling up from today's capacity of 0.01 Mt. When CO₂ is captured at ambient temperature, it has to be heated up to around 900°C for regeneration at ambient pressures, making the average levelized cost more than 200 USD/tCO₂ as of 2020, while the carbon price is hardly above 100 USD/tCO₂ – as shown in Fig. 1B.

Breakthrough technologies are needed to significantly reduce or even halve the cost of CC for its large-scale application, especially for DAC. A key may be to reduce the cost of high-temperature regeneration heat. However, neither highly efficient heat pumps nor abundant waste heat sources, such as the exhaust air of data centres, various industrial processes, and the outlet of conventional abandoned oil and gas wells, can meet the temperature requirement of CC regeneration.

Thermal energy storage (TES) is another key technology to combat climate change. TES offers unique benefits such as decoupling the heating and cooling demand from immediate power generation, and supply availability of a highly volatile renewable-dominated power grid. The global cold thermal energy storage (CTES) capacity should increase to meet the rapidly growing cooling demand. However, current CTES materials suffer from considerably low energy densities, especially for low-temperature applications, as illustrated in Fig. 1C, leaving the industry mainly relying on inefficient natural materials such as rocks and water.

Using chemical reactions is one way to boost the energy density of thermal energy storage. Compared to latent and sensible storage systems, thermochemical energy storage offers an energy density of 2-10 times higher. However, thermochemical energy storage based on reversible reactions is rarely mentioned in the literature for cold temperatures, leaving a major research gap in the area of thermal energy storage studies.

SUMMARY OF THE INVENTION

According to a first aspect of the present disclosure a method for capturing carbon dioxide (CO₂) and storing thermal energy is provided. The method comprises a capturing stage and a regeneration stage, and the method comprises the steps of: in the capturing stage, capturing CO₂ from a gas stream by a carbon capture medium, where the capture of CO₂ by the capture medium generates heat due to an exothermic reaction between CO₂ and the carbon capture medium; and in the regeneration stage, applying a source of heat to the carbon capture medium to release CO₂ from the carbon capture medium. Further, the carbon capture medium is capable of reacting

with CO₂ in an exothermic reaction to provide a carbon storage medium; during the capturing stage, the carbon capture medium is maintained at a temperature that is below a CO₂ regeneration temperature of the carbon capture medium by the application of cooling; and during the regeneration stage, the source of heat is provided to the carbon capture medium at a first temperature and exits the carbon capture medium at a second temperature, where the second temperature is lower than the first temperature.

In an embodiment, capturing CO₂ from the gas stream comprises bubbling the gas stream through the carbon capture medium.

In an embodiment, capturing CO₂ from the gas stream comprises a membrane that separates gases and liquids of the gas stream.

In an embodiment, a gas stream leaving the capturing stage has a higher temperature than the gas stream entering the capturing stage.

In an embodiment, a gas stream leaving the capturing stage has a lower humidity than the gas stream entering the capturing stage.

In an embodiment, the regeneration stage includes a step of cooling a heat source via the regeneration process.

In an embodiment, the method further comprises the step of storing the regenerated CO₂.

In an embodiment, the carbon capture medium comprises a carbon capture material or sorbent.

In an embodiment, the carbon capture medium comprises a solvent and a carbon capture material.

In an embodiment, the application of cooling the carbon capture medium comprises cooling via a cooling means.

In an embodiment, the cooling means comprises one or more of: the or a gas stream, a liquid stream, a vapour compression refrigerator, a heatpump, a chiller, an absorption chiller, an adsorption chiller, a thermal electric module, a caloric cooling system, and/or an evaporative cooling device.

In an embodiment, the application of cooling the carbon capture medium maintains a carbon capture medium temperature below an ambient temperature.

10 In an embodiment, the application of cooling the carbon capture medium maintains a carbon capture medium temperature range of from about -10 °C to about 20 °C.

In an embodiment, the source of heat applied during the regeneration stage is at or above an ambient temperature.

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In an embodiment, the carbon capture medium comprises one or more of: amine-based absorbents (for example, monoethanolamine, 2-aminoethanol, 2-(2-aminoethoxy)ethanol, 1 -amino-2-propanol, 2-amino- 1 -butanol, 2-amino-2-methyl-1-propanol, 2-amino-2-methyl-1-3-propandiol, 2-amino-2-(hydroxymethyl)-1-3propanediol, 2-(methylamino)ethanol, 2-(ethylamino)ethanol, 2-(butylamino)ethanol, 2-(tertbutylamino)ethanol, diethanolamine, bis(2-hydroxypropyl)amine, 2-(dimethylamino)ethanol, N methyl diethanolamine, diethylethanolamine, etc.) and their aquatic and organic solutions, ionic liquids, amino acid solutions (for example, arginine, 4-(2-aminoethyl)piperazine-1-yl acetic acid and 3-(2,5-dimethylpiperazine-1-yl) propanoic acid), hydroxide absorbents/alkaline solutions (for example, KOH, NaOH, Ca(OH)₂, etc.), and carbonate absorbents (for example, NH₄HCO₃, BeCO₃/Be(OH)₂).

In an embodiment, the carbon capture medium is or comprises monoethanolamine.

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According to a second aspect of the present disclosure a carbon capture and/or thermal energy storage system is provided. The system comprises a reaction vessel comprising a carbon capture medium to capture CO₂ from a gas stream, wherein the capture of CO₂ by the carbon capture medium generates heat due to an exothermic

reaction between CO₂ and the carbon capture medium, temperature control means to maintain a temperature of the carbon capture medium below a CO₂ regeneration temperature, and a regeneration vessel, fluidically coupled to the reaction vessel, and configured to elevate a temperature of the carbon capture medium to a temperature
5 at or above a CO₂ regeneration temperature of the carbon capture medium. The system is configured such that cold energy is transferred from the reaction vessel to the regeneration vessel, and/or heat energy is transferred from the regeneration vessel to the reaction vessel.

10 In an embodiment, the reaction vessel is configured such that a gas stream leaving the reaction vessel is at a higher temperature than the gas stream entering the reaction vessel.

In an embodiment, the gas stream is heated during the, or via the, exothermic CO₂
15 capture process.

In an embodiment, the reaction vessel is configured such that a gas stream leaving the reaction vessel is at a lower humidity than the gas stream entering the reaction vessel.
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In an embodiment, the gas stream is dehumidified during the, or via the, CO₂ capture process.

In an embodiment, the cold energy transferred to the regeneration vessel cools a heat
25 source via a CO₂ regeneration process.

In an embodiment, the cold energy is stored prior to a CO₂ regeneration process.

In an embodiment, the system further comprises CO₂ storage means to store the CO₂
30 released during a regeneration process.

In an embodiment, the regenerated CO₂ is utilized in downstream applications.

In an embodiment, the carbon capture medium comprises a carbon capture material or sorbent.

5 In an embodiment, the carbon capture medium comprises a solvent and a carbon capture material.

In an embodiment, the temperature control means comprises cooling via one or more of: the or a gas stream, a liquid stream, a vapour compression refrigerator, a heatpump, a chiller, an absorption chiller, an adsorption chiller, a thermal electric module, a caloric
10 cooling system, and/or an evaporative cooling device.

In an embodiment, the temperature control means maintains a carbon capture medium temperature below an ambient temperature.

15 In an embodiment, the temperature control means maintains a temperature of the carbon capture medium in a temperature range of from about -10 °C to about 20 °C.

In an embodiment, the regeneration vessel further comprises a heating means to increase a temperature of the carbon capture medium to a temperature at or above a
20 CO₂ regeneration temperature of the carbon capture medium.

In an embodiment, the heating means maintains a temperature of the carbon capture medium in a temperature range of from about 20 °C to about 30 °C.

25 In an embodiment, the heating means maintains a temperature of the carbon capture medium at or above an ambient temperature.

In an embodiment, the carbon capture medium comprises one or more of: amine-based absorbents (for example, monoethanolamine, 2-aminoethanol, 2-(2-aminoethoxy)ethanol, 1-amino-2-propanol, 2-amino-1-butanol, 2-amino-2-methyl-1-propanol, 2-amino-2-methyl-1-3-propandiol, 2-amino-2-(hydroxymethyl)-1-3propanediol, 2-(methylamino)ethanol, 2-(ethylamino)ethanol, 2-(butylamino)ethanol, 2-(tertbutylamino)ethanol, diethanolamine, bis(2-hydroxypropyl)amine, 2-(dimethylamino)ethanol, N methyl diethanolamine, diethylethanolamine, etc.) and their
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aquatic and organic solutions, ionic liquids, amino acid solutions (for example, arginine, 4-(2-aminoethyl)piperazine-1-yl acetic acid and 3-(2,5-dimethylpiperazine-1-yl) propanoic acid), hydroxide absorbents/alkaline solutions (for example, KOH, NaOH, Ca(OH)₂, etc.), and carbonate absorbents (for example, NH₄HCO₃,
5 BeCO₃/Be(OH)₂).

In an embodiment, the carbon capture medium is monoethanolamine.

According to a third aspect of the present disclosure a reaction vessel is provided. The
10 reaction vessel comprises an inlet to receive a gas stream, a carbon capture medium to capture CO₂ from the gas stream, wherein the capture of CO₂ by the carbon capture medium generates heat due to an exothermic reaction between CO₂ and the carbon capture medium, temperature control means to maintain a temperature of the carbon capture medium below a CO₂ regeneration temperature of the carbon capture medium
15 during a carbon capture stage, or to increase a temperature of the carbon capture medium above a CO₂ regeneration temperature during a regeneration stage, and an outlet to release a heated gas stream in the carbon capture stage, or release CO₂ in the regeneration stage.

20 In an embodiment, the reaction vessel further comprises a thermal recovery means to recover cold energy during the regeneration stage.

In an embodiment, the carbon capture medium comprises a carbon capture material or sorbent.

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In an embodiment, the reaction vessel further comprises CO₂ storage means to store the CO₂ released during a regeneration process.

In an embodiment, the carbon capture medium comprises a solvent and a carbon
30 capture material.

In an embodiment, the temperature control means comprises cooling via one or more of: the or a gas stream, a liquid stream, a vapour compression refrigerator, a heatpump,

a chiller, an absorption chiller, an adsorption chiller, a thermal electric module, a caloric cooling system, and/or an evaporative cooling device.

In an embodiment, the temperature control means maintains a carbon capture medium
5 temperature below an ambient temperature.

In an embodiment, the reaction vessel is configured such that a gas stream leaving the reaction vessel is at a higher temperature than the gas stream entering the reaction vessel.
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In an embodiment, the reaction vessel is configured such that a gas stream leaving the reaction vessel is at a lower humidity than the gas stream entering the reaction vessel.

15 In an embodiment, the temperature control means cools a heat source during the regeneration stage.

In an embodiment, the temperature control means maintains a temperature of the carbon capture medium in a temperature range of from about -10 °C to about 20 °C
20 during the capture stage.

In an embodiment, the temperature control means maintains a temperature of the carbon capture medium in a temperature range of from about 20 °C to about 30 °C during the regeneration stage.
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In an embodiment, the carbon capture medium comprises one or more of: amine-based absorbents (for example, monoethanolamine, 2-aminoethanol, 2-(2-aminoethoxy)ethanol, 1 -amino-2-propanol, 2-amino- 1 -butanol, 2-amino-2-methyl-1-propanol, 2-amino-2-methyl-1-3-propandiol, 2-amino-2-(hydroxymethyl)-1-3propanediol, 2-(methylamino)ethanol, 2-(ethylamino)ethanol, 2-(butylamino)ethanol, 2-(tertbutylamino)ethanol, diethanolamine, bis(2-hydroxypropyl)amine, 2-(dimethylamino)ethanol, N methyl diethanolamine, diethylethanolamine, etc.) and their aquatic and organic solutions, ionic liquids, amino acid solutions (for example, arginine, 4-(2-aminoethyl)piperazine-1-yl acetic acid and 3-(2,5-dimethylpiperazine-1-yl)

propanoic acid), hydroxide absorbents/alkaline solutions (for example, KOH, NaOH, Ca(OH)_2 , etc.), and carbonate absorbents (for example, NH_4HCO_3 , $\text{BeCO}_3/\text{Be(OH)}_2$).

- 5 In an embodiment, the carbon capture medium is monoethanolamine.

In an embodiment the second or third aspects of the present disclosure are combined with any of the embodiments described in the first aspect of the present disclosure.

10 BRIEF DESCRIPTION OF THE DRAWINGS

In the following, embodiments of the present invention will be described as non-limiting examples with reference to the accompanying drawings in which:

- 15 Fig. 1A illustrates an example of a typical chemical absorption carbon capture process;

Fig. 1B illustrates a graph of carbon capture cost against CO_2 concentration, along with a current carbon price level;

- 20 Fig. 1C illustrates an example of energy density of some CTES materials;

FIG. 2 illustrates a flowchart showing a capturing stage of a method for capturing carbon dioxide (CO_2) and storing thermal energy according to an embodiment of the present invention;

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FIG. 3 illustrates a flowchart showing a regeneration stage of a method for capturing carbon dioxide (CO_2) and storing thermal energy according to an embodiment of the present invention;

- 30 Fig. 4A illustrates an example embodiment of a system as disclosed herein operating in a cold operation mode;

Fig. 4B illustrates an alternative example embodiment of a system as disclosed herein operating in a cold operation mode;

Fig.5A illustrates an example embodiment of a system as disclosed herein operating in a hot operation mode;

- 5 Fig.5B illustrates an alternative example embodiment of a system as disclosed herein operating in a hot operation mode;

Fig.6 illustrates an example embodiment of a system as disclosed herein which may measure the reaction heat during CO₂ absorption and desorption;

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Fig.7 illustrates a process flow diagram of a system as disclosed in Fig.6;

Fig.8 illustrates a test cell of an example system as described herein;

- 15 Figs.9a and 9b illustrate experimental results of example systems as described herein in a cooling mode (Fig.9a) and in a heating mode (Fig.9b); and

Fig.10 illustrates a graph of DAC rate and CO₂ loading against temperature.

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DETAILED DESCRIPTION

- The invention relates to the concept of combined cold carbon capture and thermal energy storage, which may address the main challenges of two critical climate technologies simultaneously: 1) the high energy penalty of carbon capture (CC), and
25 2) the low energy density of thermal energy storage (TES). The invention may relate to the reduction of the operational temperature of conventional carbon capture systems to below ambient or sub-zero levels, which may allow the realization of low energy penalty CC and high energy density cold energy storage and transportation.

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As outlined herein, the present disclosure relates to a combination of two concepts, low temperature carbon capture (CC), which may also be low cost, and thermal energy storage (TES) which may be high-energy density and low temperature. The bottleneck of each technology (i.e., CC and TES), may provide for a solution to the other. Both

processes involve reversible endothermic and exothermic chemical reactions. The high energy penalty of CC due to the strongly endothermic decomposition reaction may be the most desirable property for a TES process to increase the energy density, for example, gaining heat is equivalent to releasing cold, and vice versa.

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Fig. 2 and Fig. 3 illustrate flow diagrams of a method for capturing carbon dioxide (CO₂) and storing thermal energy according to an embodiment of the invention. The method comprises a capturing stage 200 as shown in Fig. 2, and a regeneration stage 300 as shown in Fig. 3.

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In the capturing stage 200 as shown in Fig. 2, the method for capturing carbon dioxide (CO₂) and storing thermal energy comprises capturing CO₂ from a gas stream by a carbon capture medium, where the capture of CO₂ by the capture medium generates heat due to an exothermic reaction between CO₂ and the carbon capture medium.

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Accordingly, in a first step 210, the method comprises applying cooling to maintain the carbon capture medium at a temperature that is below a CO₂ regeneration temperature of the carbon capture medium. At the next step 220, the method comprises introducing a gas stream to capture CO₂ from the gas stream by a carbon capture medium. In this way, a carbon capture medium may be provided at a temperature below a regeneration temperature, which in an example embodiment may be a low temperature, and/or below an ambient temperature. The carbon capture medium may also have CO₂ absorbed within. Advantageously, this may provide for a useable source of cold (i.e. below a regeneration temperature, which may be below an ambient temperature), that can be released during a regeneration stage of the carbon capture medium as set out below.

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In the regeneration stage 300 as shown in Fig. 3, the method, for capturing carbon dioxide (CO₂) and storing thermal energy comprises releasing the CO₂ that has previously been captured as set out in method 200 of Fig. 2 as outlined above. Further, the cold stored within the carbon capture medium may be utilized. In the regeneration stage 300 the method may comprise step 310 of applying a source of heat to the carbon capture medium to release CO₂ from the carbon capture medium. The CO₂ may then be stored in a further process or step, as set out in optional step 320. Advantageously, the cold in the carbon capture medium that comprises absorbed CO₂

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may be released, such as by cooling the source of heat at step 310 as outlined herein, providing a thermal energy store.

Turning back to the capture stage 200 in Fig. 2, the carbon capture medium may be capable of reacting with CO₂ in an exothermic reaction to provide a carbon storage medium. Additionally, during the regeneration stage 300 in Fig. 3, the source of heat at 310 may be provided to the carbon capture medium at a first temperature and may exit the carbon capture medium at a second temperature, where the second temperature is lower than the first temperature.

In an example embodiment, the CC and TES processes may be combined according to the nature of their respective reactions as set out herein, where the maintaining of the carbon capture medium at a temperature below the CO₂ regeneration temperature allows for a carbon capture medium to be provided that is both reduced in temperature (i.e., storing cold energy), whilst also containing absorbed CO₂.

In an example embodiment, the carbon capture medium comprises a carbon capture material or sorbent. In an example embodiment, the carbon capture medium comprises a solvent and a carbon capture material.

In an example embodiment, the carbon capture medium is a phase change slurry (PCS), as a form of carbon capture and thermal energy storage solvent. The carbon capture medium, in the form of a solvent in this example, may partially change its phase to solid and form a solid-liquid mixture, which may also be pumpable to allow movement of the carbon capture medium around the system as described herein.

The reaction of CO₂ and the carbon capture medium is provided in more detail below. In an experimental example, monoethanolamine (MEA), one of the most widely used CO₂ sorbent, can be shown with a simplified version of the reaction as:



The equilibrium constant is defined as:

$$K_{MEA} = \frac{[CO_2] + [HCO_3^-] + [CO_3^{2-}] + [MEACOO^-]}{[MEA] + [MEA^+] + [MEACOO^-]} \quad (2)$$

Its CO₂ capture capacity increases as temperature decreases, according to M. Gupta et al., Gabrielsen et al., and Chremos et al. (Gupta, M. & Svendsen, H. F. Temperature dependent enthalpy of CO₂ absorption for amines and amino acids from theoretical calculations at infinite dilution; Energy Procedia 63, 1106–1114 (2014). Gabrielsen, J., Michelsen, M. L., Stenby, E. H. & Kontogeorgis, G. M. A model for estimating CO₂ solubility in aqueous alkanolamines. Ind. Eng. Chem. Res. 44, 3348–3354 (2005); Chremos, A. et al. Modelling the phase and chemical equilibria of aqueous solutions of alkanolamines and carbon dioxide using the SAFT-γ SW group contribution approach. Fluid Phase Equilib. 407, 280–297 (2016), all of which are incorporated herein by reference.)

Whilst MEA is described above, various groups of materials have the potential to be suitable for combined CC and TES, including but not limited to: amine-based absorbents (for example, 2-aminoethanol, 2-(2-aminoethoxy)ethanol, 1 -amino-2-propanol, 2-amino- 1 -butanol, 2-amino-2-methyl-1-propanol, 2-amino-2-methyl-1-3-propanediol, 2-amino-2-(hydroxymethyl)-1-3propanediol, 2-(methylamino)ethanol, 2-(ethylamino)ethanol, 2-(butylamino)ethanol, 2-(tertbutylamino)ethanol, Diethanolamine, bis(2-hydroxypropyl)amine, 2-(dimethylamino)ethanol, N methyl diethanolamine, Diethylethanolamine, etc.) and their aquatic and organic solutions, ionic liquids, amino acid solutions (for example, Arginine, 4-(2-Aminoethyl)piperazine-1-yl acetic acid and 3-(2,5-Dimethylpiperazine-1-yl) propanoic acid), hydroxide absorbents/alkaline solutions (for example, KOH, NaOH, Ca(OH)₂, etc.), and carbonate absorbents (for example, NH₄HCO₃, BeCO₃/Be(OH)₂).

In an example embodiment, capturing CO₂ from the gas stream at step 220 may comprise bubbling the gas stream through the carbon capture medium. Alternatively, or in addition, capturing CO₂ from the gas stream at step 220 may comprise a membrane that separates gases and liquids of the gas stream. In one embodiment, the gas stream may leave the capturing stage 200 after step 220 at a higher temperature than the gas stream entering the capturing stage, for example due to the exothermic reaction of the CO₂ absorption. However, in alternative embodiments the

gas stream may exit at the same temperature it entered, or at a cooler temperature, at least in part due to the cooling application to the capture medium at step 210. Similarly, in an embodiment, a gas stream leaving the capturing stage may comprise a lower humidity than the gas stream entering the capturing stage, for example due to
5 the cooling application at 210, however alternatively the gas stream may exit at the same or higher humidity as required.

In an example embodiment, the application of cooling the carbon capture medium at step 210 comprises cooling via a cooling means. The cooling means may comprise
10 any mechanism to cool the carbon capture medium, for example to below a regeneration temperature or below an ambient temperature as described herein. For example, the cooling means may comprise one or more of: the gas stream, where the stream of incoming gas itself may be cold and provide the requisite cooling, a separate gas stream, a liquid stream, a vapour compression refrigerator, a heatpump, a chiller,
15 an absorption chiller, an adsorption chiller, a thermal electric module, a caloric cooling system, and/or an evaporative cooling device.

In an example embodiment, the cooling as described herein may be active or from active sources, for example a vapour compression refrigerator, a heatpump, a chiller,
20 an absorption chiller, an adsorption chiller, a thermal electric module, a caloric cooling system, and/or an evaporative cooling device. Alternatively, or in addition, the cooling as described herein may be passive or from passive sources, for example by using cold sources provided or applied from outside the system, such as LNG cold, Liquid H₂ cold, Liquid air cold, etc. and/or provided by the environment in which the system
25 is sited. In example embodiments, the cooling means as described herein may be process cooling, and/or may be waste cold energy, and may be transferred by air and/or liquid as described herein.

In an example embodiment, as outlined herein the application of cooling the carbon capture medium maintains a carbon capture medium temperature below an ambient
30 temperature. For example, the application of cooling the carbon capture medium maintains a carbon capture medium temperature range of from about -10 °C or about 0 °C to about 20 °C. However, it will be understood that any capture temperature is envisaged that falls within a typical range as required for the selected carbon capture

medium, for example, to maintain a temperature of the carbon capture medium below a regeneration temperature of the carbon capture medium, and/or below an ambient temperature.

- 5 In an example embodiment, the regeneration stage, such as that described at 300 in Fig. 3, includes a step of applying a heat source 310 to heat the carbon capture medium. In an example embodiment, the source of heat applied during the regeneration stage is at or above a regeneration temperature of the carbon capture medium, and/or at or above an ambient temperature. For example, to maintain a
10 temperature of the carbon capture medium in a temperature range of from about 20 °C or about 25 °C to about 30 °C. However, it will be understood that any regeneration temperature is envisaged that falls within a typical range as required for the selected carbon capture medium, for example, to maintain a temperature of the carbon capture medium at or above a regeneration temperature of the carbon capture medium, and/or
15 at or above an ambient temperature, such that CO₂ may be regenerated from the carbon capture medium. Further, whilst reference is made to a CO₂ regeneration temperature, it will be understood CO₂ regeneration occurs at any temperature above the regeneration temperature, and this higher temperature will become the regeneration temperature. In example embodiments, any temperature, as long as it is
20 higher than the CO₂ capture temperature as described herein, can be a CO₂ regeneration temperature. In example embodiments, this temperature may be ambient temperature, or low grade heat (lower than 80 °C or 100 °C), as described herein, which may be lower than conventional high or very high temperature systems.
- 25 In example embodiments, depending on the carbon capture medium used, the cooling and/or regeneration temperature of the carbon capture medium may be about -100 °C to about 100 °C, or may be a lower or higher temperature outside of this range, and it will be understood that any temperature may be envisaged depending on the carbon capture medium used, and the CO₂ regeneration temperature of the carbon capture
30 medium.

In an example embodiment, the step 310 may comprise cooling a heat source via the regeneration process. For example, a waste heat source may be cooled by passing

the heat through the carbon capture medium containing cold energy and CO₂, such as via a heat exchanger.

5 In an example embodiment, the method further comprises the step 320 of storing the regenerated CO₂, for example, the CO₂ regenerated at regeneration stage 300 may be captured, used, and/or stored as it is released during the regeneration stage. For example, the regenerated CO₂ may be utilized in downstream applications.

10 However, it will be understood that the systems and methods disclosed herein are not limited to any specific reactions or materials. Further, it will be understood that the most suitable material should be selected for each application based on its melting point, CC potential, and latent heat as required.

15 An example embodiment of a cold operation mode carbon capture and energy storage system as disclosed herein is illustrated in Fig.4A, where a system 400 as disclosed herein may be used to store and transport cold energy. In the example embodiment, CO₂ may be absorbed and released when the cold energy is charged and discharged, respectively, which may allow the process to operate at a temperature range lower than conventional CC processes.

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The system 400 illustrated in Fig.4A comprises a capturing stage 410, which may be a cold station stage 410, and a regeneration stage 420, which may comprise a cold user stage 420. In an example embodiment, the cold station stage 410 may be configured to charge cold, and capture CO₂, whilst the cold user stage 420 may be configured to discharge cold, and release captured CO₂. The stages 410, 420 are illustrated as separate stages in Fig.4A, however it will be understood that the stages 410, 420 may be combined in alternate embodiments, for example as illustrated in Fig.4B and described herein. The capturing stage 410 of the system 400 in Fig.4A may comprise a gas inlet 430, which may facilitate the introduction of a gas stream to capturing stage 410 that may comprise a CO₂ carrying gas, which may be a cold CO₂ carrying gas, for example air, or flue gas that could be used to regasify LNG as outlined herein. The gas inlet 430 may introduce the gas stream to the capturing stage 410, which may comprise a carbon capture medium 435. In an example embodiment, the carbon capture medium 435 may comprise a medium or material that can absorb or

capture CO₂ from the gas stream, wherein the capture of CO₂ generates heat due to an exothermic reaction between CO₂ and the carbon capture medium 435. The capturing stage 410 may be maintained at a temperature that is below a CO₂ regeneration temperature of the carbon capture medium, for example by the application of cooling. The carbon capture medium 435 may therefore comprise a carbon storage medium 470.

In an example embodiment, capturing CO₂ from the gas stream 430 may comprise bubbling the gas stream through the carbon capture medium 435. Alternatively, or in addition, capturing CO₂ from the gas stream 430 may comprise a membrane that separates gases and liquids of the gas stream 430.

In the example embodiment of Fig.4A, the gas stream 430 may exit or leave the capturing stage 410 as gas exit stream 440. The gas exit stream 440 may leave the capturing stage 410 at a higher temperature than the gas stream 430 entering the capturing stage 410. In an example embodiment, the gas stream 440 leaving the capturing stage 410 may have a lower humidity than the gas stream 430 entering the capturing stage 410.

In the example embodiment of Fig.4A, the carbon capture medium may be transferred as the carbon storage medium 470 to the regeneration stage 420, becoming a carbon storage medium 455 containing dissolved or absorbed CO₂. The regeneration stage may comprise the application of a source of heat 450 to the carbon capture medium in the regeneration stage 420 such that the dissolved or absorbed CO₂ may be released from the carbon storage medium 455 in the regeneration stage 420.

In an example embodiment, the source of heat 450 may enter the regeneration stage 420 at a first temperature, and may exit the regeneration stage 420 at a second temperature 460, where the first temperature is higher than the second temperature, i.e. the source of heat is cooled as it enters 450 and then leaves 460 the regeneration stage 420. In an example embodiment, the carbon storage medium 470 transporting cold from the capture stage 410 to carbon storage medium 455 in the regeneration stage 420 may transfer the cold to the heat source 450, or put another way, may be warmed by the heat source 450. In an example embodiment, the warming of the

carbon storage medium 455 is such that it is to a level above a CO₂ regeneration temperature of the carbon storage medium 455, allowing the carbon storage medium 455 to release absorbed CO₂, which may have been absorbed in the capture stage 410 as outlined herein.

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In an example embodiment, the carbon storage medium 455 may become carbon capture medium 480, which may be transferred to the capturing stage 410 to become carbon capture medium 435. The carbon capture medium may be of a reduced CO₂ concentration, and may be hotter than carbon storage medium 470 given that the heat source 450 heated the carbon storage medium 455 in regeneration stage 420 to release CO₂. In this way, carbon capture medium 480 may transfer heat from regeneration stage 420 to capturing stage 410.

In an example embodiment, the application of a source of heat 450 may comprise a heat transfer fluid, which may enter at 450 as a hot HTF, and exit at 460 as a cold or colder HTF. In an example embodiment, the carbon storage medium 470 transferring from capturing stage 410 to regeneration stage 420 may comprise a CO₂ rich slurry, and may be cold, for example at a temperature below a CO₂ regeneration temperature of the carbon storage medium 470. In an example embodiment, the carbon capture medium 480 transferring from regeneration stage 420 to capture stage 410 may be a CO₂ lean stream of carbon capture medium 480, and may be hot, for example at a temperature above a CO₂ regeneration temperature of the carbon capture medium 480. The carbon capture medium 480 may then be transferred to capturing stage 410 as outlined herein, becoming carbon capture medium 435, and may be cooled to begin the process over.

In an example embodiment as set out above, the regeneration stage 420 may include cooling a heat source 450 via the regeneration process of the carbon storage medium 455. In an example embodiment, the process comprises regenerating CO₂ stored within the carbon storage medium 455, which may be further captured, used, and/or stored as outlined herein. For example, the regenerated CO₂ may exit the regeneration stage 420 at outlet 490 for further processing.

In an example embodiment, the carbon capture medium 435, 470, 455, 480 may comprise a carbon capture material or sorbent, and may also comprise a solvent and a carbon capture material.

5 In an example embodiment, the application of cooling of the carbon capture medium 435 at the capturing stage 410 may comprise cooling via a cooling means. In example
embodiments, the cooling means may comprise one or a combination of: the or a gas
stream, a liquid stream, a vapour compression refrigerator, a heatpump, a chiller, an
absorption chiller, an adsorption chiller, a thermal electric module, a caloric cooling
10 system, and/or an evaporative cooling device. For example, the gas stream 430 may
enter capturing stage 410 at a temperature below a CO₂ regeneration temperature of
the carbon capture medium 435, which may maintain the capturing stage 410 at the
temperature as outlined herein. Alternatively, or in addition, the capturing stage and/or
gas stream 430 and/or carbon capture medium 435 may be maintained below a CO₂
15 regeneration temperature of the carbon capture medium 435 by a cooling means such
as a separate gas stream, a liquid stream, a vapour compression refrigerator, a
heatpump, a chiller, an absorption chiller, an adsorption chiller, a thermal electric
module, a caloric cooling system, and/or an evaporative cooling device. In this way,
the carbon capture medium 435 may be maintained below a CO₂ regeneration
20 temperature whilst gas stream 430 is introduced and CO₂ is absorbed, which as
explained herein will generate heat due to the exothermic reaction between CO₂ and
the carbon capture medium 435.

In an example embodiment, the application of cooling the carbon capture medium 435
25 maintains the carbon capture medium 435 below a CO₂ regeneration temperature,
which may include maintaining the temperature below an ambient temperature, for
example, the application of cooling the carbon capture medium 435 maintains a
carbon capture medium 435 temperature range of from about -10 °C or about 0 °C to
about 20 °C. However, it will be understood that any temperature range is envisaged
30 such that the carbon capture medium 435 maintains a temperature below a CO₂
regeneration temperature, and the selected temperature will depend on the carbon
capture medium 435 in use.

In an example embodiment, the heating means or source of heat 450 applied during the regeneration stage to cause regeneration of CO₂ from the carbon storage medium 455 may be at or above an ambient temperature, from example a temperature range of from about 20 °C or about 25 °C to about 30 °C. However, it will be understood that
 5 any temperature range is envisaged such that the carbon storage medium 455 maintains a temperature at or above a CO₂ regeneration temperature, and the selected temperature will depend on the carbon storage medium 455 in use.

In an example embodiment, the carbon capture medium 435, and/or carbon storage
 10 medium 455 may be the same medium, and may comprise one or more of: amine-based absorbents (for example, monoethanolamine, 2-aminoethanol, 2-(2-aminoethoxy)ethanol, 1 -amino-2-propanol, 2-amino- 1 -butanol, 2-amino-2-methyl-1-propanol, 2-amino-2-methyl-1-3-propandiol, 2-amino-2-(hydroxymethyl)-1-3propanediol, 2-(methylamino)ethanol, 2-(ethylamino)ethanol, 2-(butylamino)ethanol,
 15 2-(tertbutylamino)ethanol, diethanolamine, bis(2-hydroxypropyl)amine, 2-(dimethylamino)ethanol, N methyl diethanolamine, diethylethanolamine, etc.) and their aquatic and organic solutions, ionic liquids, amino acid solutions (for example, arginine, 4-(2-aminoethyl)piperazine-1-yl acetic acid and 3-(2,5-dimethylpiperazine-1-yl) propanoic acid), hydroxide absorbents/alkaline solutions (for example, KOH, NaOH,
 20 Ca(OH)₂, etc.), and carbonate absorbents (for example, NH₄HCO₃, BeCO₃/Be(OH)₂).

Fig.4B illustrates an alternative example embodiment 401, which may comprise a system 401 including a combined capturing stage, and a regeneration stage 411. The
 25 combined stage 411 is illustrated in Fig.4B, however as outlined above, it will be understood that the stages 410, 420 may be separated in alternate embodiments, for example as illustrated in Fig.4A and described herein.

The combined stage 411 of the system 401 in Fig.4B may comprise a gas inlet 431,
 30 which may facilitate the introduction of a gas stream to combined stage 411 that may comprise a CO₂ carrying gas, which may be a cold CO₂ carrying gas, for example air, or flue gas that could be used to regasify LNG as outlined herein. The gas inlet 431 may introduce the gas stream to the combined stage 411, which may comprise a carbon capture medium 436. In an example embodiment, the carbon capture medium

436 may comprise a medium or material that can absorb or capture CO₂ from the gas stream, wherein the capture of CO₂ generates heat due to an exothermic reaction between CO₂ and the carbon capture medium 436. The combined stage 411 may be maintained at a temperature that is below a CO₂ regeneration temperature of the carbon capture medium, for example by the application of cooling. The carbon capture medium 436 may therefore comprise a carbon storage medium 456.

In an example embodiment, capturing CO₂ from the gas stream 431 may comprise bubbling the gas stream through the carbon capture medium 436. Alternatively, or in addition, capturing CO₂ from the gas stream 431 may comprise a membrane that separates gases and liquids of the gas stream 431.

In the example embodiment of Fig.4B, the gas stream 431 may exit or leave the combined stage 411 as gas exit stream 441. The gas exit stream 441 may leave the combined stage 411 at a higher temperature than the gas stream 431 entering the combined stage 411. In an example embodiment, the gas stream 441 leaving the combined stage 411 may have a lower humidity than the gas stream 431 entering the combined stage 411.

In the example embodiment of Fig.4B, the carbon capture medium 436 may become a carbon storage medium 456 containing dissolved or absorbed CO₂. As will be understood in the combined stage 411, this may occur as the carbon capture medium 435 captures CO₂ from the gas stream 431.

The combined stage 411 may comprise the application of a source of heat 451 to the carbon capture medium in the combined stage 411 such that the dissolved or absorbed CO₂ may be released from the carbon storage medium 456 in the combined stage 411.

In an example embodiment, the source of heat 451 may enter the combined stage 411 at a first temperature, and may exit the combined stage 411 at a second temperature 461, where the first temperature is higher than the second temperature, i.e. the source of heat is cooled as it enters 451 and then leaves 461 the combined stage 411. In an example embodiment, the carbon storage medium 435 being cooled as it absorbs CO₂

to become carbon storage medium 456 may transfer the cold to the heat source 451, or put another way, may be warmed by the heat source 451. In an example embodiment, the warming of the carbon storage medium 456 is such that it is to a level above a CO₂ regeneration temperature of the carbon storage medium 456, allowing
5 the carbon storage medium 456 to release absorbed CO₂, which may have been absorbed in the combined stage 411 as outlined herein.

In an example embodiment, the carbon storage medium 456 may become carbon capture medium 435 as it is regenerated in combined stage 411. The carbon capture
10 medium may be of a reduced CO₂ concentration, and may be hotter given that the heat source 451 heated the carbon storage medium 456 during regeneration to release CO₂.

In an example embodiment, the application of a source of heat 451 may comprise a
15 heat transfer fluid, which may enter at 451 as a hot HTF, and exit at 461 as a cold or colder HTF. In an example embodiment, during or after absorption, the carbon storage medium 436 may comprise a CO₂ rich slurry, and may be cold, for example at a temperature below a CO₂ regeneration temperature of the carbon storage medium 436. In an example embodiment, after regeneration of the carbon storage medium 456
20 the carbon storage medium 436 may be a CO₂ lean carbon capture medium 436, and may be hot, for example at a temperature above a CO₂ regeneration temperature of the carbon capture medium 436. The carbon capture medium may then be cooled as outlined herein, the begin the process over.

25 In an example embodiment as set out above, the combined stage 411 may include cooling a heat source 451 via the regeneration process of the carbon storage medium 456. In an example embodiment, the process comprises regenerating CO₂ stored within the carbon storage medium 456, which may be further captured, used, and/or stored as outlined herein. For example, the regenerated CO₂ may exit the regeneration
30 stage 421 at outlet 491 for further processing.

In an example embodiment, the carbon capture medium 436, 456, may comprise a carbon capture material or sorbent, and may also comprise a solvent and a carbon capture material.

In an example embodiment, the application of cooling of the carbon storage medium 436 at the combined stage 411 may comprise cooling via a cooling means. In example embodiments, the cooling means may comprise one or a combination of: the or a gas stream, a liquid stream, a vapour compression refrigerator, a heatpump, a chiller, an absorption chiller, an adsorption chiller, a thermal electric module, a caloric cooling system, and/or an evaporative cooling device. For example, the gas stream 431 may enter combined stage 411 at a temperature below a CO₂ regeneration temperature of the carbon capture medium 436, which may maintain the capturing stage at the temperature as outlined herein. Alternatively, or in addition, the combined stage 411 and/or gas stream 431 and/or carbon capture medium 436 may be maintained below a CO₂ regeneration temperature of the carbon capture medium 436 by a cooling means such as a separate gas stream, a liquid stream, a vapour compression refrigerator, a heatpump, a chiller, an absorption chiller, an adsorption chiller, a thermal electric module, a caloric cooling system, and/or an evaporative cooling device. In this way, the carbon capture medium 436 may be maintained below a CO₂ regeneration temperature whilst gas stream 431 is introduced and CO₂ is absorbed, which as explained herein will generate heat due to the exothermic reaction between CO₂ and the carbon capture medium 436.

In an example embodiment, the application of cooling the carbon capture medium 436 maintains the carbon capture medium 436 below a CO₂ regeneration temperature, which may include maintaining the temperature below an ambient temperature, for example, the application of cooling the carbon capture medium 436 maintains a carbon capture medium 436 temperature range of from about -10 °C or about 0 °C to about 20 °C. However, it will be understood that any temperature range is envisaged such that the carbon capture medium 436 maintains a temperature below a CO₂ regeneration temperature, and the selected temperature will depend on the carbon capture medium 436 in use.

In an example embodiment, the heating means or source of heat 451 applied during the regeneration stage to cause regeneration of CO₂ from the carbon storage medium 456 may be at or above an ambient temperature, from example a temperature range of from about 20 °C or about 25 °C to about 30 °C. However, it will be understood that

any temperature range is envisaged such that the carbon storage medium 456 maintains a temperature at or above a CO₂ regeneration temperature, and the selected temperature will depend on the carbon storage medium 456 in use.

- 5 In an example embodiment, the carbon capture medium 436, and/or carbon storage medium 456 may be the same medium, and may comprises one or more of: amine-based absorbents (for example, monoethanolamine, 2-aminoethanol, 2-(2-aminoethoxy)ethanol, 1-amino-2-propanol, 2-amino-1-butanol, 2-amino-2-methyl-1-propanol, 2-amino-2-methyl-1-3-propanediol, 2-amino-2-(hydroxymethyl)-1-
10 3propanediol, 2-(methylamino)ethanol, 2-(ethylamino)ethanol, 2-(butylamino)ethanol, 2-(tertbutylamino)ethanol, diethanolamine, bis(2-hydroxypropyl)amine, 2-(dimethylamino)ethanol, N methyl diethanolamine, diethylethanolamine, etc.) and their aquatic and organic solutions, ionic liquids, amino acid solutions (for example, arginine, 4-(2-aminoethyl)piperazine-1-yl acetic acid and 3-(2,5-dimethylpiperazine-1-yl)
15 propanoic acid), hydroxide absorbents/alkaline solutions (for example, KOH, NaOH, Ca(OH)₂, etc.), and carbonate absorbents (for example, NH₄HCO₃, BeCO₃/Be(OH)₂).

As outlined herein, the system and methods disclosed may be utilized to transport cold,
20 or store, or utilize cold, as set out above in relation to Fig.4A, and Fig.4B. In an alternative embodiment, the systems and methods disclosed herein may be utilized to transport heat, or store, or utilize heat, as set out below in relation to Fig.5A, and Fig.5B. It will be understood that the system configuration as described herein may enable transporting or heat or cold as described, or may enable the implementation of both
25 transferring heat and cold using the same configuration.

The system 500 illustrated in Fig.5A comprises a capturing stage 510, which may be a heat user stage 510, and a regeneration stage 520, which may comprise a heat station stage 520. In an example embodiment, the heat user stage 510 may be
30 configured to discharge heat, and capture CO₂, whilst the heat station stage 520 may be configured to charge heat, and release captured CO₂. The stages 510, 520 are illustrated as separate stages in Fig.5A, however it will be understood that the stages 510, 520 may be combined in alternate embodiments, for example as illustrated in Fig.5B and described herein. The capturing stage 510 of the system 500 in Fig.5A

may comprise a gas inlet 530, which may facilitate the introduction of a gas stream to capturing stage 510 that may comprise a CO₂ carrying gas, which may be a cold CO₂ carrying gas, for example indoor air that requires heating as outlined herein. The gas inlet 530 may introduce the gas stream to the capturing stage 510, which may
5 comprise a carbon capture medium 535. In an example embodiment, the carbon capture medium 535 may comprise a medium or material that can absorb or capture CO₂ from the gas stream, wherein the capture of CO₂ generates heat due to an exothermic reaction between CO₂ and the carbon capture medium 535. The capturing stage 510 may be maintained at a temperature that is below a CO₂ regeneration
10 temperature of the carbon capture medium, for example by the application of cooling. The carbon capture medium 535 may therefore comprise a carbon storage medium 570.

In an example embodiment, capturing CO₂ from the gas stream 530 may comprise
15 bubbling the gas stream through the carbon capture medium 535. Alternatively, or in addition, capturing CO₂ from the gas stream 530 may comprise a membrane that separates gases and liquids of the gas stream 530.

In the example embodiment of Fig.5A, the gas stream 530 may exit or leave the
20 capturing stage 510 as gas exit stream 540. The gas exit stream 540 may leave the capturing stage 510 at a higher temperature than the gas stream 530 entering the capturing stage 510. In an example embodiment, the gas stream 540 leaving the capturing stage 510 may have a lower humidity than the gas stream 530 entering the capturing stage 510.

25 In the example embodiment of Fig.5A, the carbon capture medium may be transferred as the carbon storage medium 570 to the regeneration stage 520, becoming a carbon storage medium 555 containing dissolved or absorbed CO₂. The regeneration stage 520 may comprise the application of a source of heat 550 to the carbon capture
30 medium in the regeneration stage 520 such that the dissolved or absorbed CO₂ may be released from the carbon storage medium 555 in the regeneration stage 520.

In an example embodiment, the source of heat 550 may enter the regeneration stage 520 at a first temperature, and may exit the regeneration stage 520 at a second

temperature 560, where the first temperature is higher than the second temperature, i.e. the source of heat is cooled as it enters 550 and then leaves 560 the regeneration stage 520. In an example embodiment, the carbon storage medium 570 transporting cold from the capture stage 510 to carbon storage medium 555 in the regeneration stage 520 may transfer cold to the heat source 550, or put another way, may be warmed by the heat source 550. In an example embodiment, the warming of the carbon storage medium 555 is such that it is to a level above a CO₂ regeneration temperature of the carbon storage medium 555, allowing the carbon storage medium 555 to release absorbed CO₂, which may have been absorbed in the capture stage 510 as outlined herein.

In an example embodiment, the carbon storage medium 555 may become carbon capture medium 580, which may be transferred to the capturing stage 510 to become carbon capture medium 535. The carbon capture medium may be of a reduced CO₂ concentration, and may be hotter than carbon storage medium 570 given that the heat source 550 heated the carbon storage medium 555 in regeneration stage 520 to release CO₂. In this way, carbon capture medium 580 may transfer heat from regeneration stage 520 to capturing stage 510.

In an example embodiment, the application of a source of heat 550 may comprise a heat transfer fluid, which may enter at 550 as a hot HTF, and exit at 560 as a cold or colder HTF. In an example embodiment, the carbon storage medium 570 transferring from capturing stage 510 to regeneration stage 520 may comprise a CO₂ rich stream, and may be cold, for example at a temperature below a CO₂ regeneration temperature of the carbon storage medium 570. In an example embodiment, the carbon capture medium 580 transferring from regeneration stage 520 to capture stage 510 may be a CO₂ lean stream of carbon capture medium 580, and may be hot, for example at a temperature above a CO₂ regeneration temperature of the carbon capture medium 580. The carbon capture medium 580 may then be transferred to capturing stage 510 as outlined herein, becoming carbon capture medium 535, and may be cooled, and/or may transfer heat to the gas stream 530 to begin the process over.

In an example embodiment as set out above, the capturing stage 510 may include heating a gas stream 530 via the CO₂ absorption process of the carbon storage

medium 535. In an example embodiment, the process comprises absorbing CO₂ from the gas stream 530 by the carbon capture medium 535, which may be further captured, used, and/or stored as outlined herein. For example, the regenerated CO₂ may exit the regeneration stage 520 at outlet 590 for further processing.

5

In an example embodiment, the carbon capture medium 535, 570, 555, 580 may comprise a carbon capture material or sorbent, and may also comprise a solvent and a carbon capture material.

10 In an example embodiment, the application of cooling of the carbon capture medium 535 at the capturing stage 510 may comprise cooling via a cooling means. In example embodiments, the cooling means may comprise the gas stream 530, which may be indoor air that requires heating, for example by being below an ambient temperature. In example embodiments, the cooling means may comprise one or a combination of:

15 the or a gas stream 530, a liquid stream, a vapour compression refrigerator, a heatpump, a chiller, an absorption chiller, an adsorption chiller, a thermal electric module, a caloric cooling system, and/or an evaporative cooling device. For example, the gas stream 530 may enter capturing stage 510 at a temperature below a CO₂ regeneration temperature of the carbon capture medium 535, which may maintain the

20 capturing stage 510 at the temperature as outlined herein. Alternatively, or in addition, the capturing stage and/or gas stream 530 and/or carbon capture medium 535 may be maintained below a CO₂ regeneration temperature of the carbon capture medium 535 by a cooling means such as a separate gas stream, a liquid stream, vapour compression refrigerator, a heatpump, a chiller, an absorption chiller, an adsorption

25 chiller, a thermal electric module, a caloric cooling system, and/or an evaporative cooling device. In this way, the carbon capture medium 535 may be maintained below a CO₂ regeneration temperature whilst gas stream 530 is introduced and CO₂ is absorbed, which as explained herein will generate heat due to the exothermic reaction between CO₂ and the carbon capture medium 535.

30

In an example embodiment, the application of cooling the carbon capture medium 535 maintains the carbon capture medium 535 below a CO₂ regeneration temperature, which may include maintaining the temperature below an ambient temperature, for example, the application of cooling the carbon capture medium 535 maintains a

carbon capture medium 535 temperature range of from about -10 °C or about 0 °C to about 20 °C. In an example embodiment, this temperature range could be achieved by introduced cold air (e.g. indoor air) that requires heating, i.e. air that is below an ambient temperature. However, it will be understood that any temperature range is envisaged such that the carbon capture medium 535 maintains a temperature below a CO₂ regeneration temperature, and the selected temperature will depend on the carbon capture medium 535 in use.

In an example embodiment, the heating means or source of heat 550 applied during the regeneration stage to cause regeneration of CO₂ from the carbon storage medium 555 may be at or above an ambient temperature, from example a temperature range of from about 20 °C or about 25 °C to about 30 °C. However, it will be understood that any temperature range is envisaged such that the carbon storage medium 555 maintains a temperature at or above a CO₂ regeneration temperature, and the selected temperature will depend on the carbon storage medium 555 in use.

In an example embodiment, the carbon capture medium 535, and/or carbon storage medium 555 may be the same medium, and may comprise one or more of: amine-based absorbents (for example, monoethanolamine, 2-aminoethanol, 2-(2-aminoethoxy)ethanol, 1 -amino-2-propanol, 2-amino- 1 -butanol, 2-amino-2-methyl-1-propanol, 2-amino-2-methyl-1-3-propandiol, 2-amino-2-(hydroxymethyl)-1-3propanediol, 2-(methylamino)ethanol, 2-(ethylamino)ethanol, 2-(butylamino)ethanol, 2-(tertbutylamino)ethanol, diethanolamine, bis(2-hydroxypropyl)amine, 2-(dimethylamino)ethanol, N methyl diethanolamine, diethylethanolamine, etc.) and their aquatic and organic solutions, ionic liquids, amino acid solutions (for example, arginine, 4-(2-aminoethyl)piperazine-1-yl acetic acid and 3-(2,5-dimethylpiperazine-1-yl) propanoic acid), hydroxide absorbents/alkaline solutions (for example, KOH, NaOH, Ca(OH)₂, etc.), and carbonate absorbents (for example, NH₄HCO₃, BeCO₃/Be(OH)₂).

Fig.5B illustrates an alternative example embodiment 501, which may comprise a system 501 including a combined capturing stage, and a regeneration stage 511. The combined stage 511 is illustrated in Fig.5B, however as outlined above, it will be

understood that the stages 510, 520 may be separated in alternate embodiments, for example as illustrated in Fig.5A and described herein.

The combined stage 511 of the system 501 in Fig.5B may comprise a gas inlet 531, which may facilitate the introduction of a gas stream to combined stage 511 that may comprise a CO₂ carrying gas, which may be a cold CO₂ carrying gas, for example indoor air that requires heating as outlined herein. The gas inlet 531 may introduce the gas stream to the combined stage 511, which may comprise a carbon capture medium 536. In an example embodiment, the carbon capture medium 536 may comprise a medium or material that can absorb or capture CO₂ from the gas stream, wherein the capture of CO₂ generates heat due to an exothermic reaction between CO₂ and the carbon capture medium 536. The combined stage 511 may be maintained at a temperature that is below a CO₂ regeneration temperature of the carbon capture medium, for example by the application of cooling. The carbon capture medium 536 may therefore comprise a carbon storage medium 556.

In an example embodiment, capturing CO₂ from the gas stream 531 may comprise bubbling the gas stream through the carbon capture medium 536. Alternatively, or in addition, capturing CO₂ from the gas stream 531 may comprise a membrane that separates gases and liquids of the gas stream 531.

In the example embodiment of Fig.5B, the gas stream 531 may exit or leave the combined stage 511 as gas exit stream 541. The gas exit stream 541 may leave the combined stage 511 at a higher temperature than the gas stream 531 entering the combined stage 511. In an example embodiment, the gas stream 541 leaving the combined stage 511 may have a lower humidity than the gas stream 531 entering the combined stage 511.

In the example embodiment of Fig.5B, the carbon capture medium 536 may become a carbon storage medium 556 containing dissolved or absorbed CO₂. As will be understood in the combined stage 511, this may occur as the carbon capture medium 535 captures CO₂ from the gas stream 531.

The combined stage 511 may comprise the application of a source of heat 551 to the carbon capture medium in the combined stage 511 such that the dissolved or absorbed CO₂ may be released from the carbon storage medium 556 in the combined stage 511.

5

In an example embodiment, the source of heat 551 may enter the combined stage 511 at a first temperature, and may exit the combined stage 511 at a second temperature 561, where the first temperature is higher than the second temperature, i.e. the source of heat is cooled as it enters 551 and then leaves 561 the combined stage 511. In an example embodiment, the carbon storage medium 535 being cooled as it absorbs CO₂ to become carbon storage medium 556 may transfer the cold to the heat source 551, or put another way, may be warmed by the heat source 551. In an example embodiment, the warming of the carbon storage medium 556 is such that it is to a level above a CO₂ regeneration temperature of the carbon storage medium 556, allowing the carbon storage medium 556 to release absorbed CO₂, which may have been absorbed in the combined stage 511 as outlined herein.

In an example embodiment, the carbon storage medium 556 may become carbon capture medium 535 as it is regenerated in combined stage 511. The carbon capture medium may be of a reduced CO₂ concentration, and may be hotter given that the heat source 551 heated the carbon storage medium 556 during regeneration to release CO₂.

In an example embodiment, the application of a source of heat 551 may comprise a heat transfer fluid, which may enter at 551 as a hot HTF, and exit at 561 as a cold or colder HTF. In an example embodiment, during or after absorption, the carbon storage medium 536 may comprise a CO₂ rich medium, and may be cold, for example at a temperature below a CO₂ regeneration temperature of the carbon storage medium 536. In an example embodiment, after regeneration of the carbon storage medium 556 the carbon storage medium 536 may be a CO₂ lean carbon capture medium 536, and may be hot, for example at a temperature above a CO₂ regeneration temperature of the carbon capture medium 536. The carbon capture medium may then be cooled as outlined herein, the begin the process over.

In an example embodiment as set out above, the capturing stage 511 may include heating a gas stream 531 via the CO₂ absorption process of the carbon storage medium 536. In an example embodiment, the process comprises absorbing CO₂ from the gas stream 531 by the carbon capture medium 536, which may be further captured, used, and/or stored as outlined herein. For example, the regenerated CO₂ may exit the regeneration stage 521 at outlet 591 for further processing.

In an example embodiment, the carbon capture medium 536, 556, may comprise a carbon capture material or sorbent, and may also comprise a solvent and a carbon capture material.

In an example embodiment, the application of cooling of the carbon storage medium 536 at the combined stage 511 may comprise cooling via a cooling means. In example embodiments, the cooling means may comprise the gas stream 531, which may be indoor air that requires heating, for example by being below an ambient temperature. In example embodiments, the cooling means may comprise one or a combination of: the or a gas stream, a liquid stream, a vapour compression refrigerator, a heatpump, a chiller, an absorption chiller, an adsorption chiller, a thermal electric module, a caloric cooling system, and/or an evaporative cooling device. For example, the gas stream 531 may enter combined stage 511 at a temperature below a CO₂ regeneration temperature of the carbon capture medium 536, which may maintain the capturing stage at the temperature as outlined herein. Alternatively, or in addition, the combined stage 511 and/or gas stream 531 and/or carbon capture medium 536 may be maintained below a CO₂ regeneration temperature of the carbon capture medium 536 by a cooling means such as a separate gas stream, a liquid stream, a vapour compression refrigerator, a heatpump, a chiller, an absorption chiller, an adsorption chiller, a thermal electric module, a caloric cooling system, and/or an evaporative cooling device. In this way, the carbon capture medium 536 may be maintained below a CO₂ regeneration temperature whilst gas stream 531 is introduced and CO₂ is absorbed, which as explained herein will generate heat due to the exothermic reaction between CO₂ and the carbon capture medium 536.

In an example embodiment, the application of cooling the carbon capture medium 536 maintains the carbon capture medium 536 below a CO₂ regeneration temperature,

which may include maintaining the temperature below an ambient temperature, for example, the application of cooling the carbon capture medium 536 maintains a carbon capture medium 536 temperature range of from about -10 °C or about 0 °C to about 20 °C. In an example embodiment, this temperature range could be achieved
5 by introduced cold air (e.g. indoor air) that requires heating, i.e. air that is below an ambient temperature. However, it will be understood that any temperature range is envisaged such that the carbon capture medium 536 maintains a temperature below a CO₂ regeneration temperature, and the selected temperature will depend on the carbon capture medium 536 in use.

10

In an example embodiment, the heating means or source of heat 551 applied during the regeneration stage to cause regeneration of CO₂ from the carbon storage medium 556 may be at or above an ambient temperature, from example a temperature range of from about 20 °C or about 25 °C to about 30 °C. However, it will be understood that
15 any temperature range is envisaged such that the carbon storage medium 556 maintains a temperature at or above a CO₂ regeneration temperature, and the selected temperature will depend on the carbon storage medium 556 in use.

In an example embodiment, the carbon capture medium 536, and/or carbon storage medium 556 may be the same medium, and may comprises one or more of: amine-based absorbents (for example, monoethanolamine, 2-aminoethanol, 2-(2-aminoethoxy)ethanol, 1 -amino-2-propanol, 2-amino- 1 -butanol, 2-amino-2-methyl-1-propanol, 2-amino-2-methyl-1-3-propandiol, 2-amino-2-(hydroxymethyl)-1-3propanediol, 2-(methylamino)ethanol, 2-(ethylamino)ethanol, 2-(butylamino)ethanol,
25 2-(tertbutylamino)ethanol, diethanolamine, bis(2-hydroxypropyl)amine, 2-(dimethylamino)ethanol, N methyl diethanolamine, diethylethanolamine, etc.) and their aquatic and organic solutions, ionic liquids, amino acid solutions (for example, arginine, 4-(2-aminoethyl)piperazine-1-yl acetic acid and 3-(2,5-dimethylpiperazine-1-yl) propanoic acid), hydroxide absorbents/alkaline solutions (for example, KOH, NaOH,
30 Ca(OH)₂, etc.), and carbonate absorbents (for example, NH₄HCO₃, BeCO₃/Be(OH)₂).

In an example embodiment, the CO₂ sorbent may be a high energy density thermochemical energy storage material and heat transfer fluid. The CC temperature,

i.e. that of the carbon capture material as described herein, may be reduced to a low temperature, for example below or close to zero degree Celsius, which may further increase the CO₂ capture capacity for ambient air for direct air capture (DAC), which typically may have a low CO₂ concentration of less than 500 ppm.

5

The typically energy-consuming regeneration process of CC technology may instead make use of a wide range of free heat sources, given that the carbon capture material is cooled. For example, the system may operate to regenerate any captured CO₂ using an ambient air temperature, if the carbon capture material is previously cooled to
10 below an ambient temperature during the capturing phase. Additionally, abundant but rarely used low-grade heat sources, such as the flue gas of steam turbines and the heat from abandoned oil and gas wells, could also be utilized in the regeneration process.

15 I will be understood that the illustrated example embodiments in Fig.4A and Fig.4B are only one potential system design that can store and transport cold energy while capturing the CO₂ at a low temperature range. Other options may include using external cooling systems to cool down the absorber/capturing stage, and using just one stage or column for cold charging and discharging at different times, for example
20 as illustrated in Fig.4B.

In an example embodiment, the same system as described herein in relation to Fig.4A and Fig.4B can also operate in a hot operation mode. In an example embodiment, the capture or absorber and regeneration or desorber stages may be engineered to be
25 interchangeable. Alternatively, or in addition, the system may be modified to operate in a hot operation mode as required.

An example embodiment of a hot operation mode is shown in Fig.5A and Fig.5B. In one example embodiment, the cold CC-TES system 400 as described in Fig.4A and
30 Fig.4B can be used to store and transport hot energy using the same facilities and material or medium. In the example embodiment of Fig.5A and Fig.5B, CO₂ may be absorbed and released when the hot energy is discharged and charged. In example embodiments, the operation temperature range can be similar, lower, or higher than conventional CC processes. The CO₂ sorbent can be a high energy density

thermochemical energy storage material and heat transfer fluid. The cold energy collected at the heat users may increase the CO₂ capture capacity. This process may be similar to a CC-TES process that uses CO₂ reaction to store heat.

- 5 In an example embodiment, if used for indoor environment conditioning, heating and/or cooling, the system may also reduce the CO₂ level in the air. In a cooling system for an indoor environment, the cold CC-TES system as described herein operating under the hot mode concept can be used to adjust indoor air quality, including reducing humidity, CO₂ concentration, and/or air temperature.

10

It will be understood that the example embodiments of the systems shown in Fig.5A and Fig.5B are only one potential system design that can store and transport hot energy while capturing the CO₂ at a lower temperature range. Other options include using external cooling systems to cool down the absorber/capturing stage ,and use
15 just one stage or column for hot energy charging and discharging at different times, for example as illustrated in Fig.5B.

- In an example embodiment, switching between the cold and hot operation modes may allow heat and cold energy to be stored and used at another time. For example, using
20 the cold operation mode to provide cold energy during the daytime, hot days, or summer, the cold CC-TES system as disclosed herein can be used to store the heat and use it for the nighttime, cold days, or winter. Using the hot operation mode, such as that disclosed in Fig.5A and Fig.5B, can provide hot energy during the nighttime, cold days, or winter, and using the cold CC-TES system, such as that disclosed in
25 Fig.4A and Fig.4B, can be used to store the cold and use it during the daytime, hot days, or summer. Hence, long time thermal energy storage can be realized.

The invention as disclosed herein may be a low-cost CC and high-energy density TES combined concept, which can be directly applied to CC plants and TES facilities.

30

The invention as disclosed herein may also provide additional advantages beyond those described herein, for example:

- Working with geothermal wells may allow in-situ underground carbon storage.
- Cold energy (e.g., from LNG, LN2, and LH2 regasification) can be delivered to high-power data centers to realize cryogenic computing that reduces both cooling and power demands.
- CO₂ can also be provided to users like soft drink factories that need both cold and CO₂.
- Synergizing with systems like liquid air energy storage systems, low-cost electricity storage and in-situ DAC can be realized.

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Hence, new applications in geothermal utilization, underground carbon storage, cooling solutions for high-power units, and next-generation grid-scale energy storage may also be provided by the invention as disclosed herein.

- 15 In an example embodiment as shown in Fig. 6, a lab-scale calorimetry was developed to measure the reaction heat during CO₂ absorption and desorption of an experimental example. The process flow diagram of the system is illustrated in Fig. 7.

20 The phase change (freezing and melting) of DI water is used to measure the accuracy of the lab-scale sub-zero temperature calorimetry and the error was found to be less than 1.5%.

A preliminary test was conducted. During the cooling, i.e. the cold charging and CO₂ absorbing stage, the test cell 810 as shown in Fig. 8 is used. The test cell 810 is filled with phase change slurry (PCS) as a form of carbon capture and thermal energy storage solvent (in this example embodiment a monoethanolamine (MEA) water solution). The filled test cell is placed in a chiller chamber 820 to reach temperature equilibrium at a cold temperature (around 0 °C in this example). The finned plates 830 attached to the front and back surfaces are used to conduct cold energy to the test cell 810. The thermal equilibrium was reached when the temperatures stopped changing, and the readings of the heat flux sensors were zero. Meanwhile, the CO₂ carrying gas (500 ppm CO₂ in N₂ in the example embodiment run or pure N₂ gas in a blank run) is purged into the system, bypassing the test cell 810. The mass flow rates

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and CO₂ concentration are measured in the mass flow rate controllers (MFCs) and gas analyzer (GA) as shown in Fig.7.

From an onset time, CO₂ carrying gas (or pure N₂ gas in the blank run) is purged into the test cell 810. By measuring the mass flow rates in the MFC and CO₂ concentration is measured in the GA, the amount of CO₂ absorbed can be determined. By measuring the heat flux in the surface heat flux sensors, the amount of heat transferred into the test cell can be determined. The side heat flux sensor is used to ensure that the test cell's 810 top, bottom, and side surfaces are adequately insulated and the heat transfer measured by the surface heat flux sensors is accurate enough. During the blank run, the heat transfer is solely due to the energy brought in by the gas stream. The heat flux difference between the test run and the blank run is due only to the absorption reaction.

During the heating, i.e. cold discharging and CO₂ desorbing stage, the test cell 810 is placed in an ambient environment to restore the temperature (around room temperature), while the other setup remains the same.

The experimental results are presented as graphs in Fig.9A and Fig.9B. It can be clearly seen that the heat flux (average of various repeated tests) during the test run with 500ppm CO₂ is significantly higher than the blank run with just N₂ for both heating and cooling, indicating that the testing results of an initial material sample have validated the hypothesis. During the cooling stage, the testing results demonstrated 1) a noticeable increase in the CTES energy density with simulated air (solid line curve) compared to CO₂ free gas (i.e. N₂ gas, or dashed curve), and 2) a significant reduction of CO₂ concentration at the outlet, both associated with the increase in the equilibrium loading of the sorbent due to reduced sorption temperature. Therefore, the hypothesis has been proven that reducing the reaction temperature can increase the CO₂ loading and absorb heat.

A preliminary system simulation was performed for the cooling mode and a graph of results is illustrated in Fig.10. The simulation is performed based on the speculated thermal performance of the MEA-water solution for temperatures outside the eligible boundaries. Therefore, the specific values of Fig.10 may include a margin of error,

however the trend is similar to the experimental measurements that reduced absorption temperature can lead to increased equilibrium loading of the sorbent.

Table 1 below includes simulation results of the cooling mode.

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Cold energy sources	Regeneration energy sources	Energy reduction	Remarks
Waste cold from cryogenics (e.g., LH ₂ , LNG, LAmmonia, etc.)	Unusable waste heat (<70°C) or hot ambient	Up to ~ 90%	Air compression work cannot be always reduced; cold energy supplied to users or wasted; DAC amount of up to ~ 40 / 60 / 100 kgCO ₂ per tonLH ₂ / LNG / LAmmonia
Conventional chillers	Conventional heat pumps	Up to ~ 80%	Cold and heat generation using heat pumps with COPs higher than 3; cold energy supplied to users.
Conventional chillers	Conventional heat pumps	Up to ~ 50%	Cold energy not supplied to users but reused for inlet air pre-cooling.

Compared to the conventional DAC process using the same sorbent, the PCS concept significantly reduces energy consumption by up to 50 to 90%.

- 10 The invention as disclosed herein may comprise one or more of the following:
- The chemical CC and TES processes may be combined into one process at reduced temperature ranges (e.g., lower than ambient or below 0°C).
 - One material may be used as both carbon capture sorbent and thermal energy storage materials. The material can be liquid, solid, or a phase change material

that entirely or partially changes the phase between liquid and solid, for example, a slurry.

- The mechanism of CC may be through chemical absorption or adsorption during the cold CC-TES process.
- 5 • The mechanism of TES may involve the reaction heat, the sensible and latent heat during the cold CC-TES process.
- The CC temperature may be reduced to a lower range compared to conventional CC operation to reduce the energy cost and increase the capture capability. For example, the capture may happen at a cold temperature (e.g.,
10 lower than ambient or below 0°C), and the regeneration may be around the ambient temperature or slightly higher.
- For the above-mentioned carbon capture process, cold energy may be produced using highly-efficient refrigeration cycles such as vapor compression, absorption chillers, and/or evaporative cooling devices. The cold energy may
15 be stored/the hot energy may be released during the carbon capture process.
- For the above-mentioned carbon release (or sorbent regeneration) process, the hot energy may be supplied using ambient air and/or abundant but rarely used low-grade heat sources, such as the flue gas of steam turbines or the heat from abandoned oil and gas wells. The cold energy may be released/the hot energy
20 may be stored during the carbon release process.
- The cold CC-TES may be suitable for a wide range of CO₂ concentrations, ranging from ambient air (<500 ppm) to 100% CO₂ concentration.
- The water content in the CO₂-carrying gas may also be removed if the operation temperature is low enough for the humidity of the inlet gas.
- 25 • The sorbent can be stored in a particular state, for example hourly, daily, and/or seasonally to provide for thermal energy storage.
- The sorbent may also be transported to deliver hot energy, cold energy and/or CO₂ to a different location to that where capture occurred as required.
- The systems and methods as described herein may also operate under a hot
30 mode to store and/or transport hot energy as described herein.

The cold CC-TES concept as described herein may reduce the cost of CC and increase the energy density of TES. Taking monoethanolamine (MEA) – the most

widely used CO₂ sorbent – as an example, its CO₂ capture capacity increases as temperature decreases. If using waste cold sources such as liquefied natural gas (LNG), liquid hydrogen (LH₂), liquid nitrogen (LN₂), or highly efficient refrigeration cycles, preliminary calculation shows it may be possible to eliminate the CC's reliance
5 on expensive high-temperature heat supply. The energy penalty can be reduced by 80% and the cost to below 160 USD/tCO₂ – the break-even point to make DAC systems profitable. Moreover, low-temperature absorption can result in a system that is more suitable for low-concentration CC, for example, DAC. For TES, the energy density can be 2x current CTES materials, which may reduce storage and
10 transportation costs.

Systems and methods described herein may provide improvements to two climate technologies with one single solution. Systems and methods as described herein may provide for:

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- Working with geothermal wells may allow in-situ underground carbon storage.
- Cold energy (e.g., from LNG, LN₂, and LH₂ regasification) may be delivered to high-power usage data centers to realize cryogenic computing that reduces both cooling and power demands.
- 20 • CO₂ may be provided to users such as soft drink factories that require both cold and CO₂.
- Synergizing with systems like liquid air energy storage systems, low-cost electricity storage and in-situ DAC may be realized.

25 The systems and methods as disclosed herein may provide for geothermal utilization, underground carbon storage, cooling solutions for high-power units, and next-generation grid-scale energy storage.

Whilst the foregoing description has described exemplary embodiments, it will be
30 understood by those skilled in the art that many variations of the embodiments can be made within the scope and spirit of the present invention.

CLAIMS

1. A method for capturing carbon dioxide (CO₂) and storing thermal energy, comprising a capturing stage and a regeneration stage, the method comprising the steps of:

in the capturing stage:

capturing CO₂ from a gas stream by a carbon capture medium, where the capture of CO₂ by the capture medium generates heat due to an exothermic reaction between CO₂ and the carbon capture medium; and

in the regeneration stage:

applying a source of heat to the carbon capture medium to release CO₂ from the carbon capture medium,

wherein:

the carbon capture medium is capable of reacting with CO₂ in an exothermic reaction to provide a carbon storage medium;

during the capturing stage, the carbon capture medium is maintained at a temperature that is below a CO₂ regeneration temperature of the carbon capture medium by the application of cooling; and

during the regeneration stage, the source of heat is provided to the carbon capture medium at a first temperature and exits the carbon capture medium at a second temperature, where the second temperature is lower than the first temperature.

2. The method of claim 1, wherein capturing CO₂ from the gas stream comprises bubbling the gas stream through the carbon capture medium.

3. The method of claim 1, wherein capturing CO₂ from the gas stream comprises a membrane that separates gases and liquids of the gas stream.

4. The method of claim 1, wherein a gas stream leaving the capturing stage has a higher temperature than the gas stream entering the capturing stage.

5. The method of any preceding claim, wherein the regeneration stage includes a step of cooling a heat source via the regeneration process.
6. The method of any preceding claim, further comprising storing the regenerated CO₂.
7. The method of any preceding claim, wherein the carbon capture medium comprises a carbon capture material or sorbent.
8. The method of any preceding claim, wherein the carbon capture medium comprises a solvent and a carbon capture material.
9. The method of any preceding claim, wherein the application of cooling the carbon capture medium comprises cooling via a cooling means.
10. The method of claim 9, wherein the cooling means comprises one or more of: the or a gas stream, liquid stream, a vapour compression refrigerator, a heatpump, a chiller, an absorption chiller, an adsorption chiller, a thermal electric module, a caloric cooling system, and/or an evaporative cooling device.
11. The method of any preceding claim, wherein the application of cooling the carbon capture medium maintains a carbon capture medium temperature below an ambient temperature.
12. The method of any preceding claim, wherein the application of cooling the carbon capture medium maintains a carbon capture medium temperature range of from about -10 °C to about 20 °C.
13. The method of any preceding claim, wherein the source of heat applied during the regeneration stage is at or above an ambient temperature.
14. The method of any preceding claim, wherein the carbon capture medium comprises one or more of: amine-based absorbents (for example,

monoethanolamine, 2-aminoethanol, 2-(2-aminoethoxy)ethanol, 1-amino-2-propanol, 2-amino-1-butanol, 2-amino-2-methyl-1-propanol, 2-amino-2-methyl-1-3-propanediol, 2-amino-2-(hydroxymethyl)-1-3propanediol, 2-(methylamino)ethanol, 2-(ethylamino)ethanol, 2-(butylamino)ethanol, 2-(tertbutylamino)ethanol, diethanolamine, bis(2-hydroxypropyl)amine, 2-(dimethylamino)ethanol, N methyl diethanolamine, diethylethanolamine, etc.) and their aquatic and organic solutions, ionic liquids, amino acid solutions (for example, arginine, 4-(2-aminoethyl)piperazine-1-yl acetic acid and 3-(2,5-dimethylpiperazine-1-yl) propanoic acid), hydroxide absorbents/alkaline solutions (for example, KOH, NaOH, Ca(OH)₂, etc.), and carbonate absorbents (for example, NH₄HCO₃, BeCO₃/Be(OH)₂).

15. The method of claim 14 wherein the carbon capture medium is or comprises monoethanolamine.

16. A carbon capture and/or thermal energy storage system, comprising:
a reaction vessel comprising a carbon capture medium to capture CO₂ from a gas stream, wherein the capture of CO₂ by the carbon capture medium generates heat due to an exothermic reaction between CO₂ and the carbon capture medium,
temperature control means to maintain a temperature of the carbon capture medium below a CO₂ regeneration temperature, and
a regeneration vessel, fluidically coupled to the reaction vessel, and configured to elevate a temperature of the carbon capture medium to a temperature at or above a CO₂ regeneration temperature of the carbon capture medium,
wherein the system is configured such that:
cold energy is transferred from the reaction vessel to the regeneration vessel, and/or
heat energy is transferred from the regeneration vessel to the reaction vessel.

17. The system of claim 16, wherein the reaction vessel is configured such that a gas stream leaving the reaction vessel is at a higher temperature than the gas stream entering the reaction vessel.

18. The system of claim 16 or claim 17, wherein the gas stream is heated during the, or via the, exothermic CO₂ capture process.
19. The system of any one of claims 16 to 18, wherein the gas stream is dehumidified during the, or via the, CO₂ capture process.
20. The system of any one of claims 16 to 19, wherein the cold energy transferred to the regeneration vessel cools a heat source via a CO₂ regeneration process.
21. The system of any one of claims 16 to 20, wherein the cold energy is stored prior to a CO₂ regeneration process.
22. The system of any one of claims 16 to 21, further comprising CO₂ storage means to store the CO₂ released during a regeneration process.
23. The system of any one of claims 16 to 22, wherein the carbon capture medium comprises a carbon capture material or sorbent.
24. The system of any one of claims 16 to 23, wherein the carbon capture medium comprises a solvent and a carbon capture material.
25. The system of any one of claims 16 to 24, wherein the temperature control means comprises cooling via one or more of: the or a gas stream, a liquid stream, a vapour compression refrigerator, a heatpump, a chiller, an absorption chiller, an adsorption chiller, a thermal electric module, a caloric cooling system, and/or an evaporative cooling device.
26. The system of any one of claims 16 to 25, wherein the temperature control means maintains a carbon capture medium temperature below an ambient temperature.
27. The system of any one of claims 16 to 26, wherein the temperature control means maintains a temperature of the carbon capture medium in a temperature range of from about -10 °C to about 20 °C.

28. The system of any one of claims 16 to 27, wherein the regeneration vessel further comprises a heating means to increase a temperature of the carbon capture medium to a temperature at or above a CO₂ regeneration temperature of the carbon capture medium.

29. The system of claim 28, wherein the heating means maintains a temperature of the carbon capture medium in a temperature range of from about 22 °C to about 30 °C.

30. The system of claim 28 or claim 29, wherein the heating means maintains a temperature of the carbon capture medium at or above an ambient temperature.

31. The system of any one of claims 16 to 30, wherein the carbon capture medium comprises one or more of: amine-based absorbents (for example, monoethanolamine, 2-aminoethanol, 2-(2-aminoethoxy)ethanol, 1 -amino-2-propanol, 2-amino- 1 -butanol, 2-amino-2-methyl-1-propanol, 2-amino-2-methyl-1-3-propandiol, 2-amino-2-(hydroxymethyl)-1-3propanediol, 2-(methylamino)ethanol, 2-(ethylamino)ethanol, 2-(butylamino)ethanol, 2-(tertbutylamino)ethanol, diethanolamine, bis(2-hydroxypropyl)amine, 2-(dimethylamino)ethanol, N methyl diethanolamine, diethylethanolamine, etc.) and their aquatic and organic solutions, ionic liquids, amino acid solutions (for example, arginine, 4-(2-aminoethyl)piperazine-1-yl acetic acid and 3-(2,5-dimethylpiperazine-1-yl) propanoic acid), hydroxide absorbents/alkaline solutions (for example, KOH, NaOH, Ca(OH)₂, etc.), and carbonate absorbents (for example, NH₄HCO₃, BeCO₃/Be(OH)₂).

32. The system of claim 31, wherein the carbon capture medium is monoethanolamine.

33. A reaction vessel, comprising
an inlet to receive a gas stream,
a carbon capture medium to capture CO₂ from the gas stream, wherein the capture of CO₂ by the carbon capture medium generates heat due to an exothermic reaction between CO₂ and the carbon capture medium,

temperature control means to maintain a temperature of the carbon capture medium below a CO₂ regeneration temperature of the carbon capture medium during a carbon capture stage, or to increase a temperature of the carbon capture medium above a CO₂ regeneration temperature during a regeneration stage, and an outlet to release a heated gas stream in the carbon capture stage, or release CO₂ in the regeneration stage.

34. The reaction vessel of claim 33, further comprising a thermal recovery means to recover cold energy during the regeneration stage.

35. The reaction vessel of any one of claims 33 to 34, wherein the carbon capture medium comprises a carbon capture material or sorbent.

36. The reaction vessel of any one of claims 33 to 35, further comprising CO₂ storage means to store the CO₂ released during a regeneration process.

37. The reaction vessel of any one of claims 33 to 36, wherein the carbon capture medium comprises a solvent and a carbon capture material.

38. The reaction vessel of any one of claims 33 to 37, wherein the temperature control means comprises cooling via one or more of: the or a gas stream, a liquid stream, a vapour compression refrigerator, a heatpump, a chiller, an absorption chiller, an adsorption chiller, a thermal electric module, a caloric cooling system, and/or an evaporative cooling device.

39. The reaction vessel of any one of claims 33 to 38, wherein the temperature control means maintains a carbon capture medium temperature below an ambient temperature.

40. The reaction vessel of any one of claims 33 to 39, wherein the reaction vessel is configured such that a gas stream leaving the reaction vessel is at a higher temperature than the gas stream entering the reaction vessel.

41. The reaction vessel of any one of claims 33 to 40, wherein the reaction vessel is configured such that a gas stream leaving the reaction vessel is at a lower humidity than the gas stream entering the reaction vessel.

42. The reaction vessel of any one of claims 33 to 41, wherein the temperature control means cools a heat source during the regeneration stage.

43. The reaction vessel of any one of claims 33 to 42, wherein the temperature control means maintains a temperature of the carbon capture medium in a temperature range of from about -10 °C to about 20 °C during the capture stage.

44. The reaction vessel of any one of claims 33 to 43, wherein the temperature control means maintains a temperature of the carbon capture medium in a temperature range of from about 20 °C to about 30 °C during the regeneration stage.

45. The reaction vessel of any one of claims 33 to 44, wherein the carbon capture medium comprises one or more of: amine-based absorbents (for example, monoethanolamine, 2-aminoethanol, 2-(2-aminoethoxy)ethanol, 1 -amino-2-propanol, 2-amino- 1 -butanol, 2-amino-2-methyl-1-propanol, 2-amino-2-methyl-1-3-propandiol, 2-amino-2-(hydroxymethyl)-1-3propanediol, 2-(methylamino)ethanol, 2-(ethylamino)ethanol, 2-(butylamino)ethanol, 2-(tertbutylamino)ethanol, diethanolamine, bis(2-hydroxypropyl)amine, 2-(dimethylamino)ethanol, N methyl diethanolamine, diethylethanolamine, etc.) and their aquatic and organic solutions, ionic liquids, amino acid solutions (for example, arginine, 4-(2-aminoethyl)piperazine-1-yl acetic acid and 3-(2,5-dimethylpiperazine-1-yl) propanoic acid), hydroxide absorbents/alkaline solutions (for example, KOH, NaOH, Ca(OH)₂, etc.), and carbonate absorbents (for example, NH₄HCO₃, BeCO₃/Be(OH)₂).

46. The reaction vessel of claim 45, wherein the carbon capture medium is monoethanolamine.