Highly efficient thermoelectric air conditioner with kilowatt capacity realized by ground source heat-exchanging system

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Highlights
The proposed GeoTEAC system could output kW cooling/heating capacity with COPs over 3
The GeoTEAC system is more economically and eco-friendly than conventional GSHP system
The GeoTEAC system could cut CO₂ emission and contribute to carbon emission peak in China

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Highly efficient thermoelectric air conditioner with kilowatt capacity realized by ground source heat-exchanging system

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SUMMARY
The enormous need for refrigeration of modern human life has inevitably aggravated the environmental crisis worldwide. To date, there are very few refrigeration technologies available beholdering both harmless refrigerants and high efficiency. Here, we proposed a geothermal-thermoelectric air conditioning system (GeoTEAC) with refrigerant-free and high energy efficiency through synergistically combining the merits of thermoelectric effect and ground source heat exchanging system. The system showed competitive cooling and heating COPs of 5.83 and 2.92, respectively, with kilowatt capacity, which are 3–4 times higher than that of previously reported thermoelectric air-conditioning setups. For a conceptual scenario, we demonstrated the lowest TEWI values for the GeoTEAC system among different air-conditioning types. Our work provides sustainable and climate-friendly solutions to realize worldwide emission peaks and carbon neutralization.

INTRODUCTION
Environment and energy are unquestionably two main issues challenging the sustainable development of modern human life (Global Energy Trends, 2021 Edition; Key World Energy Statistics 2021, 2021; Wang et al., 2021; Zheng et al., 2019). Particularly, the global warming resulting from emissions of CO2 and other greenhouse gases is causing some imperceptible but harmful changes to the earth’s climate, such as increasing droughts, floods, and hurricanes, etc. (Chu et al., 2016) Among all the sources of energy consumption and climate changes, enormous need for cooling of modern life is particularly influential. According to proposals to enhance European climate ambition published by Umweltbundesamt in May 2021, HFC emissions in the European Union (EU) amounted to 112 million tons CO2 equivalent in 2018. This is equivalent to 2.2% of the EU’s total greenhouse gas emissions, and primary sources of HFC emissions came from refrigeration and air-conditioning (Daniel de Graaf et al., 2021). In addition, the data from the report IEA2020 showed that nearly 8.5% of the total electricity worldwide was consumed by space cooling in 2019, contributing about 1 Gigatonne CO2 emissions and could be tripled by 2050 (The Future of Cooling: Opportunities for energyefficient air conditioning, 2018; Is cooling the future of heating?, 2020). Various refrigerants (CFCs, HCFCs, and HFCs) widely used in the conventional vapor compression air conditioners (VCAC or HVAC) or fridges are not only detrimental to the ozonosphere but also contributing significant greenhouse gases.

Though natural refrigerants, such as hydrocarbons, carbon dioxide, ammonia, and water, could be possible alternatives to synthetic refrigerants to eliminate the environmental issues, challenges in terms of toxicity, flammability, and high technology barriers are severely inhibiting its large-scale usage (Ayub, 2010). Thus, in addition to continuously improving the efficiency of HVAC system and searching for low-global warming potential (GWP) refrigerants, it is of great importance to develop refrigerant-free and high energy efficient cooling techniques for most of countries, which is also one of the main goals of the Montreal Protocol and the Paris agreement (Cooling Emissions and Policy Synthesis Report, 2020; Heath, 2017; Wu et al., 2013).

To present, several new refrigeration technologies with refrigerant-free designs have been developed to potentially lessen the environmental impacts, for instances, magnetocaloric (Li et al., 2019), electrocaloric (Mischenko et al., 2006), elastocaloric (Qian et al., 2019), thermoacoustic (Backhaus and Swift, 1999), and
barocaloric refrigerations (Manosa et al., 2010). However, none of these technologies have been fully implemented in daily household cooling usage, which are mainly limited by various technical disadvantages and small cooling/heating capacities (Ismail et al., 2021). In contrast, thermoelectric air-conditioning (TEAC)—an all-solid heat pumping technique based on narrow bandgap semiconductors—has attracted much attention in the past two decades, benefiting from its no moving parts, silence, high reliability (life span up to 25 years), and nearly maintenance-free operation (Bell, 2008; Venkatarathnam, 2009).

Compared with the two-phase working liquid in HVAC systems, electrical current is the only equivalent refrigerant in thermoelectric-cooling/heating cycle, thus showing great simplicity and flexibility of TEAC. The related energy conversion efficiency of thermoelectric materials is determined by a dimensionless parameter, named as the figure of merit $zT = S^2aT/k$, where $S$ is the Seebeck coefficient, $a$ is the electrical conductivity, $k$ is the thermal conductivity, and $T$ is the absolute temperature (Altenkirch, 1911). To calculate the COPs of thermoelectric materials, a temperature gradient $\Delta T$ is normally needed to be assigned (Rowe 2005).

$$\text{COP}_{\text{TE}} = \frac{S_{\text{eff}}(T_h - \Delta T) - I^2R - K\Delta T}{PR + S_{\text{eff}}\Delta TI},$$

(Equation 1)

where $S_{\text{eff}}$ is the effective Seebeck coefficient, $K$ is the total thermal conductance, $R$ is the total resistance, $I$ is the input electric current and $T_h$ is the hot side temperature of the thermoelectric module. The higher the $zT$ values of the thermoelectric materials, the smaller the $\Delta T$ along the thermoelectric legs and higher the COPs of the thermoelectric modules. Nowadays, thermoelectric devices have been widely used in optical communication and photoelectricity, medical instruments, car seats and fridges, and many other systems for thermal management (Basu and Singh, 2021; Disalvo, 1999; Savage, 2009). Clearly, one common feature of the aforementioned applications is that the cooling/heating capacities are generally less than 100 W, which is mainly restricted by the cost and low COPs of TE modules under a large temperature gradient (Snyder et al., 2021; Vining, 2009).

A critical factor to determine COPs of thermoelectric coolers is the heat exchanging efficiency. Different from conventional HVACs where COPs does not increase too much under smaller temperature gradients, COPs of TEACs could reach very high values under small temperature gradients (Wang et al., 2010). With today’s best commercial thermoelectric modules (Bi$_2$Te$_3$-based material with $zT$ around 1 at 300 K), the peak COP of a thermoelectric module can reach as high as 8 under a temperature gradient of 5 K (Rowe, 1995). For this purpose, various heat exchanging schemes, including water-cooling systems (Cheng et al., 2011; Lim and Jeong, 2018), phase change material systems (Zhao and Tan, 2014), and evaporative cooling systems (Tipsaenporm et al., 2012) have been proposed for TEACs, and their COPs indeed improved by 20% to 40%, despite being still lower in the range of 0.34 to 2.59 (Baheta et al., 2019). Together with these advanced heat-exchanging systems, thermoelectric air conditioning systems have been leveled up to building applications, with several styles like thermoelectric radiant panel ceiling (Shen et al., 2013), air ducts (Irshad et al., 2017), cooling facades (Prieto et al., 2017), etc. Another popular route for TEAC application is to integrate it with renewable energy sources, such as photovoltaic panel to form a self-powering loop to create zero energy buildings (Sarbu and Dorca, 2018). Nevertheless, in the aforementioned applications, huge challenges stemming from high cost, small capacity, and low COPs have severely hindered the broader application of the thermoelectric refrigeration technique.

**Geothermal-thermoelectric air-conditioning (GeoTEAC) system**

By coincidence, the widely distributed shallow geothermal energy of underground earth—being a vast thermal energy reservoir with a near-constant temperature of about 18°C all year round (Vienken et al., 2019)—could be an ideal heat-exchanging source for TEAC. Currently, the ground source heat pump (GSPH) is the dominant way to exploit shallow geothermal energy and features rich COP than an air source heat pump (Gondal, 2021). However, the traditional GSPHs generally need be equipped with a compressor (refrigerant-based vapor compression technique) to compensate for the low-grade geothermal energy. In this work, we proposed a new type of building air-conditioning system (named as GeoTEAC) by combining the merits of TEAC with the ground source heat pump (GSPH)—a two-stage air-conditioning system where the renewable geothermal energy synergistically works as a heat exchanger (part of GSPH)—as well as a heat sink for thermoelectric modules (part of TEAC) as schematically shown in Figure 1A. Distinct from the GSPH, GeoTEAC uses thermoelectric modules to compensate for the low-grade geothermal heat...
and thus being completely free of harmful refrigerants. Furthermore, GeoTEAC could realize distributed control, with cooling, heating, or ventilation modes being separately available for different terminal applications (Figure 1A and Video S1 in the Supplemental information).

We constructed a prototype GeoTEAC, including two fan-coils of different sizes (one is connected to the underground water and the other one is connected to a thermoelectric block, which is composed of in total 16 thermoelectric modules sandwiched by upper and lower water tanks (Figure S1). Although the lower water tank is connected with heat exchangers buried in the underground heat exchange zone, the upper water tank is connected to one of the fan-coils, exchanging heat between air and water (Figure 1A). When GeoTEAC works, cold/hot air in the room first blows through the 1st fan-coil filled with 18°C groundwater to get pre-warming/cooling, then passes the 2nd fan-coil, which is also filled with water but being circulated within the upper water tank of the thermoelectric block to get its heat further compensated (Figures 1A and S1). With this setup, we achieve system-cooling COPs ranging from 4.3 to 1.9 for the input electrical power from 147 W to 472 W, outputting a maximum 897 W cooling capacity (Figure 1B). Similarly, under heating mode for the electrical power range from 91 W to 376 W, the measured system-heating COPs varies from 2.8 to 2.3 (Figure 1B). Based on an analytical model we developed, we anticipate that with an optimization of the input power of each thermoelectric module in the GeoTEAC system, a significant cooling/heating capacity of 1 horsepower (≈ 2300 W) could be realized with very high system COPs of 3 (Figure 1B).
For traditional thermoelectric refrigeration, it is difficult to obtain large capacity and COP values simultaneously because large capacity often means large temperature difference—\( \Delta T \). As described in Equation (1), the larger the \( \Delta T \), the lower the COP. The solid lines in Figure 1B show system COPs of GeoTEAC (16 TE modules) with \( \Delta T = 12 \) K for the cooling mode, and \( \Delta T = 15 \) K for the heating mode. Note that the experimentally measured system COPs (blue and red solid dots for cooling and heating mode, respectively) are higher than that of theoretical simulations in the range of small input electric power. This is because in the range of small input electric power, the as-fabricated prototype GeoTEAC could hold smaller \( \Delta T \) than that of simulation (in real experiment, the \( \Delta T \) range across the TE modules is 2.2–12 K under cooling mode and 2.5–15 K under heating mode, respectively). For TE air-conditioning systems, the smaller the \( \Delta T \) across the TE modules, the higher the COPs of TEAC, thus leading to a higher experimental system COPs of GeoTEAC. This means the shade regions of Figure 1B are working windows of the as-fabricated prototype GeoTEAC, and these regions are closely depending on the real dimensions of GeoTEAC. The GeoTEAC achieves a balance between capacity and COP owing to the excellent heat dissipation, maintaining a lower temperature difference while having a relatively large cooling/heating capacity. Meanwhile, the air exchanges heat with the 1st fan-coil before exchanging heat with the 2nd fan-coils of the thermoelectric block. This strategy can significantly improve the utilization rate of shallow geothermal energy, thus improving the COPs of the whole system.

To indicate the overall environmental impact from an air-conditioning system during its operation, the total equivalent warming impact (TEWI) is normally used (Makhnatch and Khodabandeh, 2014), whereas lower values of TEWI indicate less emissions of CO\(_2\). TEWI considers the impact of direct and indirect emissions on global warming and is calculated as the sum of two parts: the direct impact of refrigerants released during the service life of the equipment, and the indirect impact of CO\(_2\) emissions from fossil fuels used to generate electric energy to run the equipment throughout the service life. Here, we consider an application scenario of a villa of around 400 m\(^2\), which roughly needs an overall heating/cooling load \( Q \) of 25 kW. Different kinds of air-conditioning types, such as split room air conditioner (with refrigerant types of R22, R410a, and R32), centralized air-conditioning system (air source heat pump ASHP and ground source heat pump GSHP), and thermoelectric air-conditioning system (TEAC), are compared with our GeoTEAC system (Table S1). The main results are shown in Figure 1C. Although both mini-split ACs and central HVACs have around 10%–20% direct CO\(_2\) emission contribution depending on different GHG properties of refrigerants, TEAC and our GeoTEAC system have zero direct emissions. Given that the total space of the villa—400 m\(^2\)—needs cooling/heating, the centralized air-conditioning system has higher energy efficiency and lower TEWI value than those of split air-conditioning techniques, because the cooling tower could enable the condenser to work at a lower temperature (Ma and Wang, 2009). TEAC system has the highest TEWI values because of the fact that TEACs generally have small COPs (about 2 under the optimized design) (Cosnier et al., 2008). As demonstrated in Figure 1B, our GeoTEAC could achieve higher system COPs and could realize distributed usage, meaning only heating or cooling only where and when needed. As shown in Figure 1C, TEWI of GeoTEAC is already competitive with that of the conventional central air conditioner. But, if only 50% of the space needs air-conditioning, our GeoTEAC will have the smallest TEWI value among all the considered cooling techniques. Although traditional central air-conditioning could also adjust the cooling/heating capacity according to user needs, their peak COP usually only occurs at 85% of the designed maximum capacity of the whole building. However, our GeoTEAC could operate with an optimal efficiency in the full range of occupancy of the entire building.

**GeoTEAC system of genus I and II**

Previously, in most TEACs, people were using a fin-fan design to dissipate the heat/cold load of thermoelectric modules to air and a water tank to inject/eject the corresponding heat (Riffat and Qiu, 2006; Wang et al., 2007). Based on this design, we first constructed the Genus I GeoTEAC (Figure S2). The terminal unit of Genus-I GeoTEAC consists of one 1st order fan coil connecting with underground water and one 2nd order heat-exchanging unit of TE block (in total 8 TE modules are used in Genus-I GeoTEAC), which are sandwiched between upper fin-fans and lower water tank (Figure S2). With this design, warm/cold air first gets precooling/heating with the 1st order fan coil and then gets compensated cooling/heating via the fin-fans of the 2nd order TE block. To accurately characterize the cooling and heating performance of the GeoTEAC system, we built a standard enthalpy difference setup (Figures 2A and S3), where the in-house temperature (from 0 to 40°C) and humidity (30%–70%) can be precisely controlled. Under the cooling mode for a working condition of ambient temperature set at 25°C, we achieved a cooling capacity of 501 W–739 W in total as the increasing of input electric power from 92 W to 642 W, with corresponding system CO-Ps ranging from
5.45 to 1.15 (Figure 2B). Similarly, under the heating mode for a working condition of ambient temperature set to \(20^{\circ}C\) to \(14^{\circ}C\), we achieved a heating capacity of 145 W to 1015 W in total as the increasing of input electric power from 61 W to 696 W, with corresponding system COPs ranging from 2.61 to 1.46 (Figure 2D). Anomalously, in the heating mode, because the air temperature is higher than that of the circulating water (set at \(18^{\circ}C\) to \(14^{\circ}C\)), the first fan-coil is prohibited from functioning. Meantime, the total input power contains the power of the fan (46 W); therefore, the system COP has a peak of 2.61 at the power of about 81 W.

In addition, we also carried out measurements for the intermediate ambient temperatures under cooling (starting from \(35^{\circ}C\) to \(25^{\circ}C\)) and heating (starting from \(0^{\circ}C\) to \(20^{\circ}C\)) modes. It was observed that under the cooling mode, with higher ambient temperatures, our GeoTEAC can provide bigger system cooling COPs and a larger capacity (Figure S4). Similarly, under the heating mode, when the lower ambient temperatures were set, the higher system heating COPs and capacity of GeoTEAC could be reached (Figure S5). Besides, we also observed that by increasing the airflow rate of GeoTEAC, higher COPs and heating/cooling capacity could be achieved, meaning better heat exchanging efficiency was realized (Figure S6).

To get more insight into the determining factors of COPs in GeoTEAC, we extracted direct COPs of TE modules as functions of the applied electric current for the cooling and heating mode, respectively (Figures 2C and 2E). As the electric current increases, the experimental COPs of TE modules intersect with several theoretical COP lines with different assumed temperature gradients, indicating that the real \(\Delta T\) across the TE modules is becoming larger as the input electric current increases. For the Genus-I GeoTEAC, we observed the \(\Delta T\) across the TE modules under cooling mode varying between 5 K and 25 K, whereas under heating mode between 10 K and 40 K (insets of Figures 2C and 2E). Clearly, with the increasing of input electric power, the input electric current for each TE module is also increasing, thus leading to a larger \(\Delta T\) across the TE modules and ultimately resulting in relatively smaller system COPs of GeoTEAC.

The origin of large \(\Delta T\) across the thermoelectric modules lies in the heat-exchanging design of fin-fan structure on top of the TE modules. These fin-fans are generally made of aluminum alloy and have low
heat-exchanging efficiency (Figure S2), thus being difficult to hold smaller $\Delta T$. To this consideration, we further invented a Genus-II GeoTEAC system by using an internally connected water tank and fan coil to replace the fin-fans of Genus-I GeoTEAC (Figure 3A and Video S2 in Supplemental information). Compared with the aluminum alloy-based fin-fan structure, for one reason, water has a large heat capacity being perfect heat-collecting medium and for another the 2nd fan coil could more effectively dissipate the heating/cooling of thermoelectric modules (Figure S1). Similar COP and cooling/heating capacity measurements were done for the Genus-II GeoTEAC system and the main results are shown in Figures 3B–3E.

Surprisingly, significant high system COPs and heating/cooling capacity were demonstrated. Within the same input electric power, Genus-II GeoTEAC achieved a cooling capacity from 506 W to 958 W with corresponding system cooling COPs ranging from 5.83 to 1.43 and a heating capacity from 248 W to 1252 W with corresponding system heating COPs varying from 2.92 to 1.85 (Figures 3B and 3D). The enhanced system COPs of Genus-II GeoTEAC can be further confirmed by the real $\Delta T$ analysis across the TE modules. The $\Delta T$ drops across the TE modules are between 0 K and 18 K under the cooling mode (inset of Figure 3C) and between 0 K and 28 K under the heating mode (inset of Figure 3D). In comparison to that of Genus-I GeoTEAC, GeoTEAC of Genus-II had 28%–30% less temperature drops across the TE modules, consequently contributing around 8% COP and around 30% cooling/heating capacity enhancement, respectively.

**DISCUSSION**

Regardless of Genus-I or Genus-II, the total system cooling/heating capacity or COPs are intrinsically composed of two parts. One part is from the 1st order fan coil heat-exchanging unit and the other part comes from the heat-exchanging unit of the thermoelectric block. For fixed working conditions of cooling mode (ambient temperature at 25°C) and heating mode (ambient temperature set at 20°C), the
cooling/heating contribution from the 1st part is more or less fixed (actually no contribution for the heating mode). Therefore, the COPs of the GeoTEAC system are mainly determined by the corresponding COPs of thermoelectric modules. As shown in Figures 2C, 2E, 3C, and 3E, two strategies could be applied to improve its COPs. One approach is to decrease temperature differences across the TE modules, which has been confirmed by the measured results of Genus-I and Genus-II GeoTEACs. Another approach to enhance efficiency is to decrease the input power of a single TE module. The COPs of TE modules change with the applied electric current (Figures 2C, 2E, 3C, and 3E) and show peaks at small input electric current. This means that we should let the TE modules work under a smaller input electric current, unfavorably resulting in smaller output capacity by a single module. To ensure the same or even higher cooling/heating capacity, increasing the number of thermoelectric modules is thus necessary. For Genus-I GeoTEAC, the increasing number of TE modules will require a larger contact area of the fin-fans, as a consequence of an unrealistic large terminal unit. However, for Genus-II GeoTEAC, where the 2nd TE block could be separately installed, it is not necessary to change the size of terminal units.

In reality, the improvement of the performance of Genus II over Genus I underpinned the previously mentioned two approaches, meaning both smaller $\Delta T$ and input electric current were realized in the Genus-II GeoTEAC. As previously noted, in GeoTEAC of Genus-II, smaller $\Delta T$ was realized than that of Genus-I. But if we make a theoretical calculation of COPs of Genus-I with the observed $\Delta T$ of Genus-II, we actually could not replicate the results of Genus-II (Figures 4A and 4B). It is because in Genus-II, we are using 16 TE modules, being twice that of Genus-I. Consequently, the input power of a single TE module is below that of Genus I at the same total input power, leading to higher COPs of TE modules in the Genus-II GeoTEAC.

The typical input power of a commercial room air conditioner is 1–2 HP, corresponding to 2000–4000 W cooling/heating capacity, respectively. To achieve this objective and high system COPs of 3, the GeoTEAC definitely requires more TE modules. Here, we define an effective heat dissipation area equaling...
Asingle TE Module, where \( N \) is the total number of TE modules and \( A_{\text{single TE module}} \) is the effective heat dissipation area of a single TE Module. Within our theoretical model (STAR Methods), we anticipate that effective heat dissipation areas of \( 0.24 \, \text{m}^2 \) and \( 1.0 \, \text{m}^2 \) are needed to realize 1 HP and 2 HP heating with COPs around 3, respectively (Figure 4C). Similarly, effective heat dissipation areas of \( 0.8 \, \text{m}^2 \) and \( 1.1 \, \text{m}^2 \) are needed to build 1 HP and 2 HP cooling with COPs around 3, respectively (Figure 4C).

Besides the smaller \( \Delta T \) and lower input electric current are needed to guarantee high COPs of GeoTEAC, material advancement in term of \( zT \) values of thermoelectric modules would definitely enhance the overall system COPs of GeoTEAC. We anticipate the maximum cooling and heating COPs as functions of average \( zT \) values (\( \langle zT \rangle_{\text{avg}} \)) of thermoelectric materials (Figure 4D). Under cooling mode, the maximum COP of the GeoTEAC system could reach 6 at \( \langle zT \rangle_{\text{avg}} = 2.0 \) for \( \Delta T \) of 12 K and more than 9 for \( \Delta T \) of 8 K. Similarly, under the heating mode, the maximum COP of the GeoTEAC system could reach 5 at \( \langle zT \rangle_{\text{avg}} = 2.0 \) for \( \Delta T \) of 18 K and more than 7 for \( \Delta T \) of 12 K. In our current setup, commercially available Bi\(_2\)Te\(_3\)-based TE modules were used, with average \( zT \) being about 0.9. As demonstrated in this work, the system COPs and the output capacity of our GeoTEAC system are already competitive with those of vapor compression air-conditioning. With further development of thermoelectric materials (for instance, \( \langle zT \rangle_{\text{avg}} \) of TE materials are in the range of 1.5–2 at 300 K), GeoTEAC with higher COPs of 5–6 could be achieved.

In addition, we assessed the capital cost of the developed terminal GeoTEAC unit and compared the overall initial investment between traditional GSHP and GeoTEAC with an envisaged application of a 400 m\(^2\) villa (Figure S7, Tables S3 and S4). For the initial investment, the cost/performance ratio of GeoTEAC is about 10% less than that of conventional GSHP, which is mainly because of the high prices of large-scale vapor compression heat. In addition, GeoTEAC is only in its infancy and its cost/performance ratio would be continually lowered down with the advancing of thermoelectric materials and techniques, such as the recent breakthrough in next-generation thermoelectric cooling modules based on Mg\(_3\)(Sb,Bi\(_2\))\(_2\) materials, which is only 10% to that of the conventionally used Bi\(_2\)Te\(_3\) system in terms of the materials cost (Yang et al., 2022). Moreover, because the thermoelectric modules can be driven by direct current, with GeoTEAC, we could literally construct a net-zero-emission building via combining with photovoltaics and lithium energy storage system without DC-AC converters (illustrated by the Video S3 in Supplemental information).

To present the overall features of GeoTEAC in a more physically intuitive manner, we compared the quietness, cost-effectiveness, COP, unit capacity, technical readiness level (TRL), and CO\(_2\) reduction among the conventional TEAC, GSHP, and our GeoTEAC in a radar assessment map (Figure 5A, Tables S6–S10). Compared to previous reported TEAC, GeoTEAC is more cost-effective, offers better control on CO\(_2\) reduction, and could realize kilowatt cooling/heating capacity with a high system COP above 4.0. Compared to GSHP, on one hand, GeoTEAC system has zero refrigerants leading to less impact on greenhouse gas (GHG) emissions and ozone layer depletion; however, on the other hand, GeoTEAC system has less noise, could realize distributed cooling/heating control, and being more economic saving.
Furthermore, a development route of total required capacity for space cooling and related CO₂ emission is summarized for the market of China in the time span from 2010 to 2050. As can be seen in this figure, with a baseline scenario, AC-related CO₂ emissions reach the peak value of 591 Mt in 2035 and will reach 386 Mt in 2050 (Karali et al., 2020). However, under a simple prediction model (Tables S11 and S12), implementation of GeoTEAC in certain scale (scenario 1 and scenario 2) would not only cut the relevant CO₂ emissions but also shift the emission peak earlier from the year of 2035 to 2030 in China (Figure 5B).

In summary, our work provides a feasible route for the thermoelectric refrigeration to be used in a large-scale cooling/heating capacity of kilowatts with high COPs around 3 via synergistically combining the merits of ground source heat pumping technique and thermoelectric cooling/heating effects. Complete refrigerant-free design, high working COPs, together with distributed cooling/heating merits of GeoTEAC guarantee a low TEWI index, being the smallest among current popular building cooling techniques. We anticipate that the overall system COPs of GeoTEAC could be further enhanced to 6, once the better thermoelectric materials with higher \( zT \) are developed. When the GeoTEAC system is integrated with clean energy such as the photovoltaic cells, hopefully we are proposing a path to zero emissions with all renewable sources, ready for a variety of space cooling or heating applications.

LIMITATIONS OF THE STUDY

Our analyses are subject to several limitations. First, the actual temperature differences across the thermoelectric modules in our GeoTEAC system shown in insets of Figures 2C, 2E, 3C, and 3E, were estimated by measuring the COPs of thermoelectric modules. Because it is varying in a dependence of input electric current, it is not suitable to use it to directly calculate the relevant COPs. Therefore, for the theoretical COPs simulation presented in Figure 1B, we have assumed fixed temperature differences for the cooling and heating mode, respectively. Second, the capital cost of our GeoTEAC system and the traditional GSHP system in this article are based on the goods market of Beijing in China. Third, the model of CO₂ emission prediction proposed in this article considers the fact that the GWP and CO₂ emission factor would decline from year to year, but the COP revolutions of conventional VCACs from year to year were not considered.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

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SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.isci.2022.104296.

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AUTHOR CONTRIBUTIONS
G.D.L., B.L.W., and H.Z.Z. designed the work. Q.L.L., G.D.L., Z.K., and H.Z.Z. fabricated the prototype GeoTEAC. Q.L.L., F.L.W., G.D.L., and B.L.W. carried out the performance measurement of GeoTEAC and analyzed the data. Q.L.L., J.W.Y., and H.T.Z. characterized the material properties of thermoelectric modules. Q.L.L., G.D.L., B.L.W., and H.Z.Z. wrote the manuscript with editing from all authors.

DECLARATION OF INTERESTS
H.Z., Z.K., and G.L., filed a patent (CN patent application no. ZL2020218081358 and ZL2020108690797) on this invention.

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STAR METHODS

KEY RESOURCES TABLE

| MATERIALS or RESOURCES | RESOURCES | IDENTIFIER |
|------------------------|-----------|------------|
| Other                  |           |            |
| Thermoelectric devices | Xianghe Orient Electric Co., Ltd | TEC1-12709 |
| Water tanks            | Xianghe Orient Electric Co., Ltd | 6.2 cm*6.2 cm*1 cm; 12.4 cm*6.2 cm*1 cm |
| Fan-coils              | TSINGHUA TONFANG | 90 cm*20 cm*6.5 cm |
| Devices casing         | TSINGHUA TONFANG | N/A |
| Heat-conducting grease | SHIN - ETSU | x23-7762 |
| Circulating pump       | Shenzhen Old Fisherman Industrial Co., Ltd | J-5000 |
| Controller             | SENQi     | VE-1000    |
| Standard enthalpy difference Laboratory | Tsinghua university | 5 kW |
| Software and algorithms | Python    | PyCharm.2020.2.5 |

RESOURCE AVAILABILITY

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Materials availability
All data and materials needed to evaluate the conclusions in the paper are present in the article or the supplemental information.

Data and materials availability
All data needed to evaluate the conclusions in the paper are present in the article or the supplemental information.

EXPERIMENTAL MODEL AND SUBJECT DETAILS

Performance measurement of GeoTEAC system
In order to accurately characterize the cooling and heating performance of GeoTEAC system, we built a standard enthalpy difference setup (Standards of GB/T 7725–2004, GB/T 17758-2010), where the in-house temperature (from 0 to 40 °C) and humidity (30%–70%) can be precisely controlled, as shown in Figures 2A and S3. In the measurement process, the terminal thermoelectric air-conditioning unit of GeoTEAC is fixed to a thermally insulating box with constant air pressure. A chiller is used to provide 18 °C circulating water to simulate shallow geothermal energy. The output cooling/heating capacity of GeoTEAC system is calculated by measuring the temperature differences and flowrate of circulating water after passing through the terminal unit. The testing principles of the GeoTEAC system are based on equations of \( \text{COP}_{\text{cooling}} = \frac{Q_h}{P} \) and \( \text{COP}_{\text{heating}} = \frac{Q_c + P}{P} \), where \( \text{COP}_{\text{cooling}} \) and \( \text{COP}_{\text{heating}} \) are the cooling and heating efficiency, respectively. \( P \) is the input electric power. For the cooling mode, the \( Q_h \) is the heating power of TE module injected into water, which is calculated by the specific heat capacity of water multiplying the temperature difference and flow rate of circulating water flowing through the heat dissipation water tank. Similarly, for Heating mode, \( Q_c \) is the cooling power inhaled from circulating water, and the calculating approach is in the same as cooling mode.
Simulation of GeoTEAC performance

The coefficient of cooling performance (COP) of a thermoelectric module used in GeoTEAC can be calculated by:

\[
COP_{TE - \text{cooling}} = \frac{Q_{c,TE}}{I} = \frac{S_{np}Tl - \frac{1}{2}R^2 + K(\Delta T)}{FR + S_{np}(\Delta T)L}.
\]  

(Equation 2)

Where \( S_{np} \) is the effective Seebeck coefficient, \( K \) is the total thermal conductance, \( R \) is the total resistance, \( I \) is the input electric current and is \( Tl \) the hot side temperature of the thermoelectric module. The total input power of the TE module \( P_{TE} \) was calculated by:

\[
P_{TE} = N p = N (\hat{F} R + a_{np} \Delta T)\].

(Equation 3)

Then, the cooling COP of the GeoTEAC system can be expressed as:

\[
COP_{\text{System - cooling}} = \frac{Q_{c,TE} + Q_{1,1st} - (P_{fan} + P_{\text{water pump}})}{P_{TE} + P_{fan} + P_{\text{water pump}}}.
\]  

(Equation 4)

Where, the \( Q_{1,1st} \) is the contribution of the 1st fan coil that set as 351.8 W, which corresponds to experimental data. \( P_{fan} \) and \( P_{\text{water pump}} \) are the fan and water pump power and consistent with the experimental data of 41.81 W and 30 W, respectively.

Similarly, the heating COP of a thermoelectric module used in GeoTEAC can be calculated by:

\[
COP_{TE - \text{heating}} = \frac{S_{np}Tl + \frac{1}{2}R^2 - K(\Delta T)}{FR + S_{np}(\Delta T)L}.
\]  

(Equation 5)

Then, the heating COP of the GeoTEAC system can be expressed as:

\[
COP_{\text{System - heating}} = \frac{Q_{b,TE} + (P_{fan} + P_{\text{water pump}})}{P_{TE} + P_{fan} + P_{\text{water pump}}}.
\]  

(Equation 6)

Where, \( Q_{b,TE} \) is the contribution of TE module involving the heat absorbed from water and input power of TE module \( P_{TE} \).

From the Equation (3), the electric current can be obtained

\[
I = \frac{-a_{np} \Delta T + \sqrt{a_{np}^2 (\Delta T)^2 - 4Rnp}}{2R}.
\]  

(Equation 7)

Substitute Equation (7) to Equations (2) and (3), we can get the dependence relationship of TE COP on the number of TE modules.

Here we define an effective heat dissipation area as:

\[
S_{\text{eff}} = N \times A_{\text{single TE Module}}.
\]  

(Equation 8)

Where, \( A_{\text{single TE Module}} \) is the area of a single TE module around 0.003844 m\(^2\).

Considering Equations (2), (3), (4), (5), (6), (7), and (8), the relation of the GeoTEAC system COP and effective heat dissipation area \( S_{\text{eff}} \) can be obtained and presented in Figure 4C.

The \( I_t \) is electric current when the TE module obtained the maximum COP,

\[
I_t = \frac{(S_h - S_p)(\Delta T)}{R \sqrt{1 + ZT - 1}}.
\]  

(Equation 9)

substituting Equation (9) into Equations (2) and (5), we could get the maximum COPs of TEAC, \( COP_{\text{max, cooling}} \) and \( COP_{\text{max, heating}} \):

\[
COP_{\text{max, cooling}} = \frac{Tl \sqrt{1 + ZT} - \frac{\Delta T + Tl}{Tl}}{\Delta T \sqrt{1 + ZT + 1}}
\]  

(Equation 10)

and
METHOD DETAILS

Genus I
The terminal unit of Genus-I GeoTEAC has a size of 60 cm × 120 cm × 18 cm, consisting of one 1st order fan coil connecting with underground water and one 2nd order heat exchanging unit of TE block (in total 8 TE modules, TEC1-12709), which are sandwiched between upper fin-fans and lower water tank. With this design, warm/cold air first gets pre-cooling/heating with the 1st order fan coil and then gets compensated cooling/heating via the fin-fans of the 2nd order TE block. In our GeoTEAC system, we are using the commercial-available TE modules. The relevant material properties are listed in Table S2.

Genus II
In the Genus-II GeoTEAC system, we are using an internally connected water tank and fan coil to the thermoelectric block, which is composed of in total 16 thermoelectric modules sandwiched by upper and lower water tanks (Figure 3A). Compared to aluminum alloy-based fin-fan structure, for one reason, water has a large heat capacity being perfect heat-collecting medium and for another the 2nd fan coil could more effectively dissipate the heating/cooling of thermoelectric modules. Similarly, when GeoTEAC works, cold/hot air in the room first blows through the 1st fan-coil filled with 18°C groundwater to get pre-warming/cooling, then passes the 2nd fan-coil, which is also filled by water but being circled within the upper water tank of the thermoelectric block, to get its heat further compensated.

Testing condition
In the measurement process of GeoTEAC, the air flow rate and room humidity were strictly controlled in the standard enthalpy laboratory. For instance, for the cooling performance measurement (room temperature fixed at 25°C), a dry bulb temperature of 25°C, a wet bulb temperature of 15°C, and an air flow rate of 287 m³ h⁻¹ were used. In addition, the humidity was kept very low so that there was no condensation under all test conditions, thus the impact of humidity on the measurements can be neglected. In the heating mode, the preheating only exists in a transition stage from the building air temperature below 18°C to the set temperature (such as 20°C), and the water in the preheating coil will be disconnected when the air temperature reaches 18°C. The amount of Q_c,1st is measured from liquid flow by the formula of \( Q_{c,1st} = C_{water} \cdot Q_{water} \cdot (T_2 - T_1) \), where \( C_{water}, Q_{water}, T_2 \) and \( T_1 \) are the heat capacity, water flux of 1st coil, and the temperature of inlet water and outlet water, respectively.

Cost analysis
The cost analysis report was calculated for a real-world space-cooling application for a 400 m² villa, based on the goods consumption market of China. The cost of GeoTEAC is about 10% less than conventional ground source heat pumps. However, precisely estimating the cost of each component is difficult because the price is closely related to geological structure, house design and the local price of goods, and so on.

Radar chart
The six axes of the radar chart of Figure 5 classifies into five grades in one-to-one correspondence with COP. The other parameters are converted into five grades in the following Tables S6–S10.

COP: Coefficient of performance
Unit capacity: Unit capacity refers to the capacity of conventional size equipment.

TRL: Technology Readiness Levels (TRL) are usually used to assess the maturity of a new technology. TRL information from the UK House of Commons, Technology and Innovation Centres, Science and Technology Committee.

CO₂ reduction: CO₂ reduction grade evaluated by the TWEI value.

Quietness: Quietness grade evaluated by the decibel scale
Cost effectiveness: Cost effectiveness is evaluated by the initial cooling/heating capacity (cost per kW).

**CO₂ reduction**

The reduction of CO₂ emission drive from the emission factor, \( \omega \), i.e., emission per unit installed capacity of GeoTEAC is lower than that of traditional HVAC. The \( \omega \) was calculated by the equation of

\[
\omega = \frac{[L + (1 - \beta) \times \varphi \times \text{GWPR}22 + P_E \times a_{CO_2}]}{C_i \cdot L},
\]

where \( \beta \) is annual leakage rate and recovery percentage in the system assumed as 5% and 90%, respectively. GWPR22 is the GWP value of R22, i.e., 1760, which is currently the most used refrigerant. The \( \varphi \) is the ratio of refrigerants newly used to R22 after GWP decreases due to refrigerant technology improvement and policies. \( P_E \) and \( C_i \) are the corresponding electric power consumed and installed capacity, and the \( a_{CO_2} \) is carbon dioxide emission factor. The \( \varphi \) and \( a_{CO_2} \) decrease year by year and list in Table S12.