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Developing a Hybrid Air Conditioning System by Channelizing Shallow Geothermal and Solar Energy for Adsorption-Compression

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ABSTRACT

Utilizing solar thermal energy or waste heat, adsorption chillers have emerged as pivotal air-conditioning systems in net zero buildings. Traditional models, operating at 50°C with a cooling tower at 33°C, exhibit suboptimal energy efficiency, yielding chilling water temperatures of merely 18~20°C. In this study, we propose leveraging a shallow geothermal energy system, operating at a cooler 22°C, to supplant the conventional cooling tower. By doing so, the coefficient of performance of the adsorption chiller can be enhanced from 0.18 to 0.4. We present two distinct adsorption-compression hybrid systems tailored for different seasons: Mode A, harnessing solar thermal energy to power the adsorption chiller for cold storage, thereby mitigating the load on the compression chiller during nocturnal operation; Mode B, generating 16°C chilling water to cool the compression chiller's condenser, thereby boosting compressor efficiency by 22%. Given that key construction components of villa-type green buildings already integrate shallow geothermal and solar thermal energy systems, the estimated minimum payback period for implementing the hybrid system stands at 2.1 years.

INTRODUCTION

Air conditioning systems rank among the top three energy-consuming appliances in many countries. In Taiwan, electrical energy consumption accounts for roughly 50% of the total consumption in both commercial and residential buildings. Enhancing the performance of air conditioning is imperative in light of future carbon market trends and the development of green buildings. Among various research domains, sorption chillers have garnered significant interest due to their adaptability to solar energy or waste heat sources. These systems operate by allowing the refrigerant (typically water) to evaporate and cool down to 7–18°C within a vacuum environment. The adsorbent then absorbs the vaporized refrigerant (water vapor) to sustain the vacuum state. During the regeneration stage, the refrigerant vapor is desorbed from the adsorbent using waste heat or solar thermal energy. The vapor is then condensed back into liquid form in the condenser, completing the cycle. Typically, such systems operate continuously with a two-bed switching structure. However, their thermal drive system efficiency falls short of traditional vapor compression systems, resulting in larger system volumes and higher costs for the same cooling capacity. Nonetheless, the thermal energy-driven nature of sorption chillers remains attractive.

Typically, buildings only have access to low-temperature solar thermal energy (< 90°C). Consequently, the evaporator temperature of heat-driven sorption chillers is relatively high, approximately 13–18°C. Meanwhile, compressor systems can easily produce 7–12°C cooling water. In recent years, scholars have explored hybrid systems that utilize cold energy from sorption chillers to cool the condenser of traditional vapor compression systems, thereby improving efficiency. For instance, Giuseppe E. Dino et al. experimentally analyzed a hybrid sorption–compression chiller for cooling and refrigeration, achieving energy savings of 15% to 25% compared to a standalone compression chiller. Gado et al. theoretically investigated the feasibility of a solar energy-driven hybrid adsorption–compression cooling system, achieving a 62.5% reduction in electricity consumption with a payback period (PBP) of 9.65 years when photovoltaic solar energy drives the compressor.

Lowering the temperature during the adsorption process can enhance the adsorbent's performance and increase the coefficient of performance (COP) of the adsorption chiller. However, the adsorption heat released when the adsorbent absorbs vapor raises its temperature, diminishing adsorption performance. Thus, the adsorption heat must be dissipated with cooling water. In an adsorption chiller, the cooling water for the adsorption bed is typically connected to the condenser, making its temperature crucial for overall performance. S. Rosiek and F.J. Batlles utilized shallow geothermal energy instead of a cooling tower in a solar-assisted absorption chiller, achieving a 31% improvement in total efficiency by using 20-meter-deep shallow geothermal water with a temperature of 22°C. Shallow geothermal energy offers lower operational energy consumption compared to cooling towers, making it highly suitable for villa-type green buildings.

In Taiwan, shallow geothermal temperatures are significantly cooler than ambient temperatures. The high humidity and temperature environment in Taiwan negatively affect cooling tower performance, resulting in higher cooling water temperatures (32–35°C) during the summer, thereby deteriorating adsorption chiller performance. Shallow geothermal energy can be sourced from groundwater, lakes, or water in the raft foundation of buildings, making it readily available for single-family villa-type construction. Consequently, integrating shallow geothermal energy can achieve higher efficiency in adsorption chillers due to the lower cooling water temperatures it provides.

In this study, we investigate a commercial adsorption chiller driven by solar energy and shallow geothermal energy, coupled with a conventional vapor compression system. Two series connection modes are explored based on lifestyle habits. Mode A employs a cold storage method, where solar thermal energy powers the adsorption chiller during the day to pre-cool water in a bucket from 25 to 15°C. At night, the vapor compression system further lowers the cooling water temperature in the bucket to 8°C, which is then utilized as an air conditioning cooling source. Mode B utilizes both solar and shallow geothermal energy to drive the adsorption chiller. The chilled water from the adsorption chiller cools the condenser of the vapor compression system, resulting in a high-efficiency hybrid system and significant energy savings. To the best of our knowledge, empirical research on solar thermal energy and shallow geothermal energy, operating as low as 50 and 22°C respectively, has not been extensively studied. The use of adsorption chillers to replace cooling towers and produce lower cooling water temperatures is particularly suitable for villa-type green buildings in hot and humid regions.

METHODS

The operational principle of an adsorption chiller is depicted in Fig. 1, featuring a dual adsorption bed configuration. Within the evaporator, refrigerant water undergoes vaporization under vacuum conditions to generate chilled water (7–18°C). Linked to the evaporator, the adsorption bed adsorbs the vaporized refrigerant to sustain the vacuum state, facilitating further refrigerant water evaporation. However, this adsorption process releases energy, elevating the adsorbent's temperature and diminishing adsorption efficiency. Thus, cooling water (18–35°C) is introduced to cool the adsorbent. Regeneration occurs in a separate adsorption bed connected to a condenser, where cooling water (18–35°C) is also utilized to maintain low temperatures. During regeneration, hot water (50–90°C) prompts desorption of water vapor from the adsorption bed, which subsequently condenses back into liquid form within the condenser. The vapor then returns to the evaporator via a valve to complete the cycle.

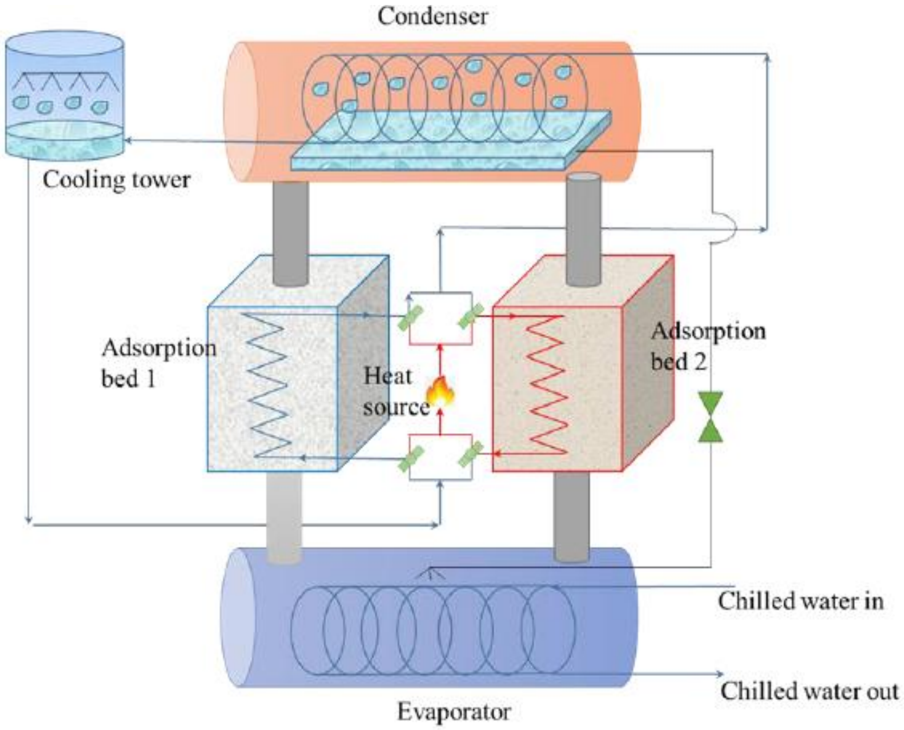


Fig. 1. Working principle of adsorption chiller.

Shallow geothermal energy represents a natural cooling resource, manifesting in soil or water with a consistent temperature approximately 3 meters below the surface. Such environments naturally revert to their initial temperature state after a period of rest. As illustrated in Fig. 2, consider a groundwater layer situated 25 meters below the ground, maintaining a stable temperature of 22°C year-round. In this study, circulating groundwater from a recharge well is linked to a vapor-compressed chiller as cooling water. The groundwater is pumped from the charge well to the vapor-compressed chiller and then returned to the recharge well. Additionally, a shallow geothermal cooling system is employed to dissipate heat generated by the condenser and adsorption bed of the adsorption chiller, replacing the conventional cooling tower (32–35°C). A commercial adsorption chiller (SorTech, Germany) is employed, with all water inlets and outlets equipped with temperature-measuring devices and linked to a data recorder. The electric power coefficient of performance (COPel), commonly applied to traditional vapor compression chillers, is utilized to evaluate performance and energy-saving potential, with W representing electric power.

RESULTS AND DISCUSSIONS

During summer, when people are typically away for work during the day, the demand for air conditioning is minimal. Solar energy, abundant in summer, allows the excess hot water generated by solar collectors during the day to power the adsorption chiller, pre-cooling chilled water in a bucket from approximately 19 to 15°C. Subsequently, during nighttime operation, the chilled water temperature can further drop to 7°C with the double-effect heat pump. This process serves as a form of solar thermal storage. Given the ample supply of hot water from solar energy for daily living and the high cooling demand in Taiwanese summers, the double-effect heat pump primarily operates to produce chilled water at night. Shallow geothermal energy proves more efficient in dissipating heat from the condenser of the vapor compression chiller than traditional cooling towers (32–35°C), thus achieving power-saving objectives. The operational principle of Mode A is illustrated in Fig. 3.

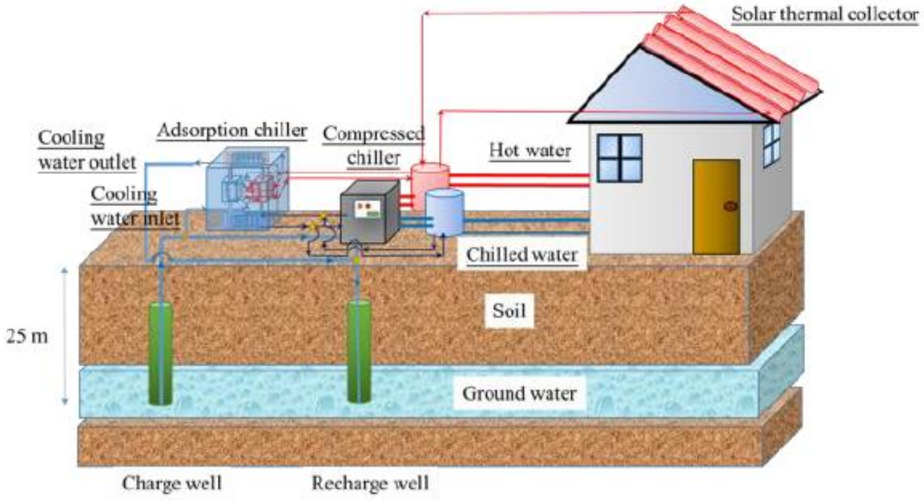


Fig. 2. Principle of solar energy-driven adsorption–compression hybrid air conditioning system.

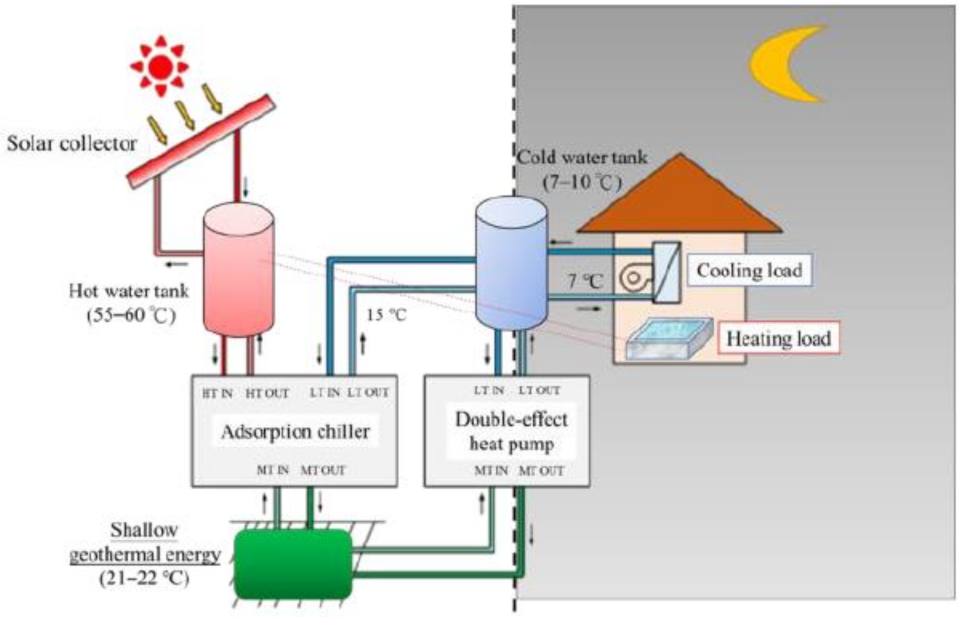


Fig. 3. Operating principle of Mode A.

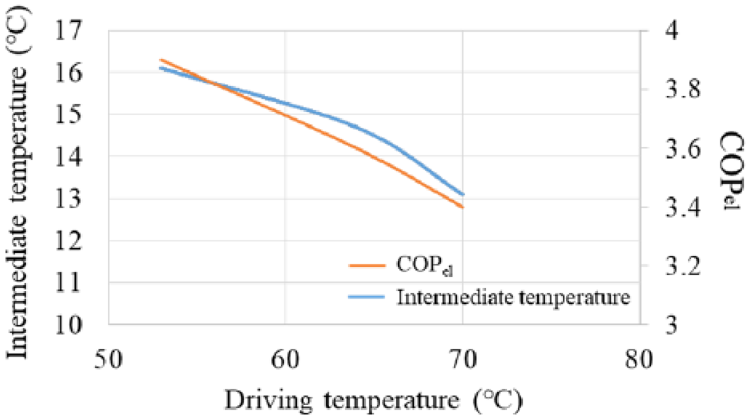


Fig. 4. Desiccant wheel test (Regeneration: 50°C).

Test results depicted in Fig. 4 reveal that higher driving temperatures correspond to lower chilled water temperatures in the tank during the day, indicating higher stored cold energy levels. Setting the final chilled water temperature at 7°C results in decreased cooling capacity for the vapor compression chiller as the temperature difference between inlet and outlet water diminishes. Despite a slight reduction in power consumption, the COPel decreases with decreasing intermediate temperature. During peak daytime loads in summer, high cold water demand elevates air conditioning system power consumption. Abundant solar and shallow geothermal energy drive the adsorption chiller to produce cooling water at 15°C, used to dissipate heat from the vapor compression chiller condenser. This cascade system enhances the COPel of the overall air conditioning system, reducing power consumption. Compared to traditional cooling towers operating at 33°C, shallow geothermal energy at 22°C exhibits substantial energy-saving potential. The operational principle of Mode B is depicted in Fig. 5.

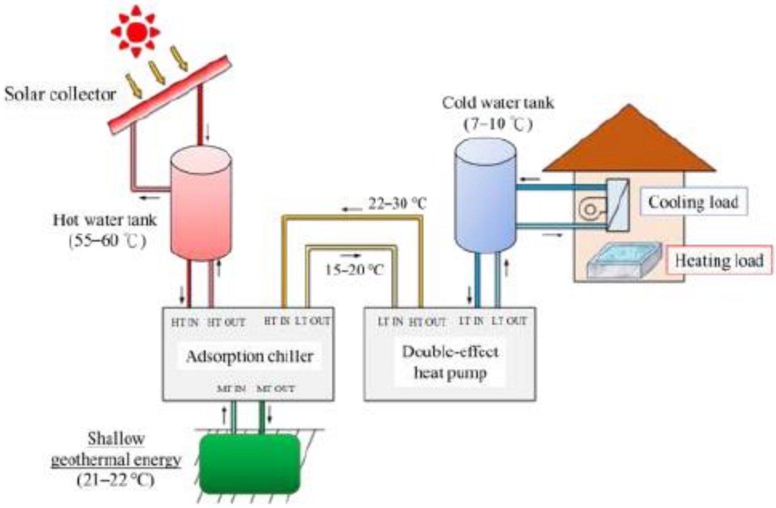


Fig. 5. Operating principle of Mode B.

Fig. 6 presents test results for the hybrid system in Mode B at a driving temperature of 63°C. The minimum chilled water outlet temperature from the adsorption chiller is 14.8°C, with an average temperature of 15.7°C. The average return water temperature is 19.2°C, resulting in an average cooling capacity of 3.92 kW. Notably, heat dissipation performance is excellent. Observations indicate that initially, the cooling capacity provided by the adsorption chiller exceeds the heat released from the dual-effect heat pump.

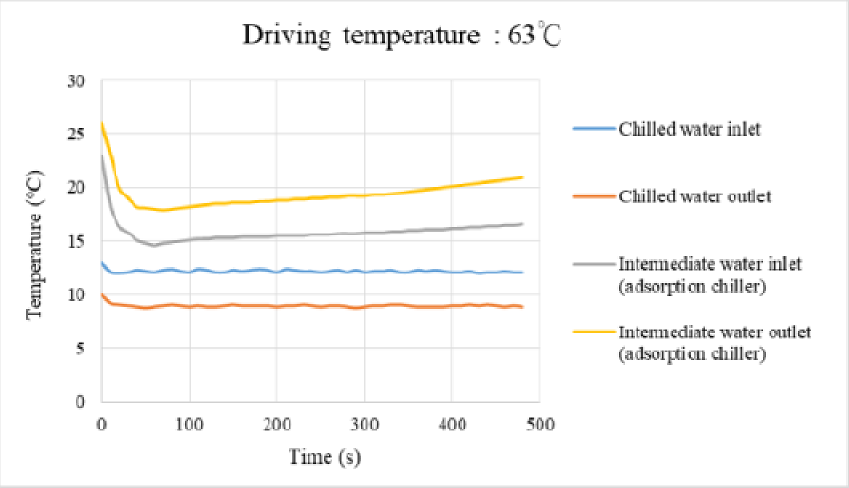


Fig. 6. Hybrid system Mode B (driving temperature 63°C

However, after 3 minutes, the intermediate water temperature begins to rise due to decreased cooling capacity of the adsorption chiller. When a cooling tower with a temperature of 30–32°C dissipates condenser heat in the compression system, the cooling COPel of the pure compression system is approximately 2.06. Fig. 7 illustrates the COPel of the Mode B hybrid system under different driving temperatures, showing an increase in COPel with increasing hot water temperature due to improved heat dissipation efficiency. The maximum COPel value observed is 4.06 at a driving temperature of 77°C, significantly reducing energy consumption of the vapor compression chiller.

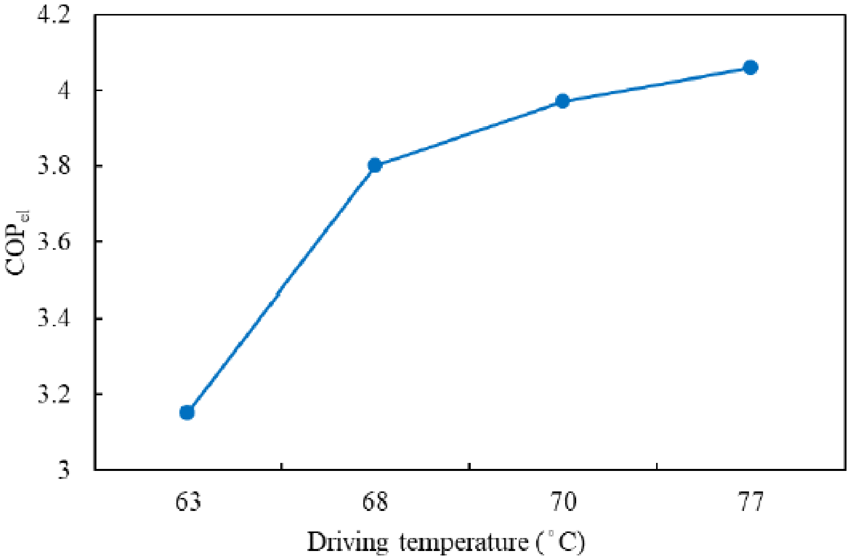
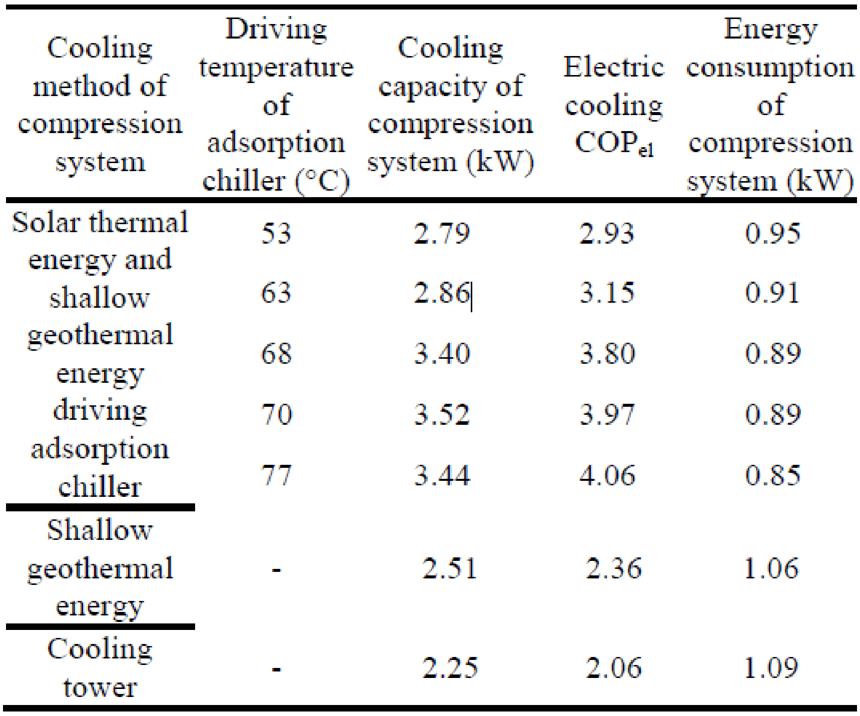


Fig. 7. Effects of driving temperature on COPel of the hybrid system.

TABLE I. COMPARISON AMONG COOLING METHODS OF COMPRESSION SYSTEM



Cooling method of compression system	Driving temperature of adsorption chiller (°C)	Cooling capacity of compression system (kW)	Electric cooling COP_{el}	Energy consumption of compression system (kW)
Solar thermal energy and shallow geothermal energy driving adsorption chiller	53	2.79	2.93	0.95
	63	2.86	3.15	0.91
	68	3.40	3.80	0.89
	70	3.52	3.97	0.89
	77	3.44	4.06	0.85
Shallow geothermal energy	-	2.51	2.36	1.06
Cooling tower	-	2.25	2.06	1.09

Table 1 summarizes experimental data for different driving temperatures of the adsorption chillers in the Mode B hybrid system. The compression system's energy consumption using a cooling tower at 30–32°C is high, with COPel approximately 2.06 due to aging equipment. Integration of shallow geothermal energy, with a temperature of 22°C, instead of a cooling tower enhances compression system performance by approximately 14%, reaching a COPel of 2.36. In the Mode B hybrid system, the intermediate water temperature at a driving temperature of 63°C is approximately 15°C, resulting in a COPel increase for the compression system to 3.15, surpassing cooling tower and shallow geothermal energy system performance by 52% and 33%, respectively.

Economic analysis reveals that the initial cost of adsorption chillers is notably high, with a payback period (PBP) exceeding 10 years. However, given that essential components of adsorption chillers include heat exchangers, adsorbents, and valves, mass production could potentially equalize costs with conventional compression chillers. Moreover, the Mode B hybrid system can reduce initial costs and achieve a favorable PBP of 2.1 years by enhancing cooling energy and reducing compressor system design capacity. Solar thermal and shallow geothermal energy systems are already integrated into villa-type buildings, mitigating initial cost concerns. Consequently, adsorption chillers hold significant application potential in villa-type constructions.

CONCLUSION

The existence of solar thermal hot water systems and shallow geothermal energy in villa-type buildings renders an economic analysis showing a potential payback period of 2.1 years. Leveraging low-temperature hot water (50–60°C) and shallow geothermal energy (20–22°C) to power adsorption chillers resolves inefficiencies of cooling towers in high-temperature, high-humidity regions. The compressor system's power consumption savings reach 12.8% at a driving temperature of 53°C and 16.5% at a driving temperature of 64°C, promising significant efficiency improvements.

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