Analysis of Different Technologies to Increase the Applicability Domain of Solar Powered Absorption Heat Pumps for Heating Applications

1 Abstract

Solar powered absorption heat pumps (SPAHPs) are an emission-free technology that could be used in domestic heating and hot water applications. SPAHPs are based on the absorption heat pump (AHP) technology and driven by solar energy, allowing for heating without any need for combustion or the use of large amounts of electric energy. Despite the favourable environmental aspects, this technology is not commonly used in heating applications due to four major challenges: unreliability due to unstable solar energy supply; low applicability due to insufficient solar energy resources at installation sites; low heating performance at low power source temperatures; and low heating performance at low ambient temperatures. In this review, the general working principle of the SPAHP is introduced, the major challenges that prevent wider application are outlined and different technologies and their working principles to overcome these challenges are presented and analysed. Further, the individual technologies are compared to each other according to the extent to which they can mitigate the issues arising from the challenges. It is found that amongst all introduced approaches the advanced AHP-CHP parallel system is the only device capable of overcoming all challenges and thus a promising technology to increase the applicability domain of SPAHPs for heating applications.

2 Introduction

In 2022, nearly 50% of the total energy consumed by buildings was used for space heating or hot water applications, accounting for 4100 Mt of CO_2 emissions. Despite the growing numbers of sustainable heating applications, fossil fuels still provide more than 60% of the heating energy. (IEA, 2023) Heat pumps have an enormous potential to contribute to global sustainability efforts and have been labelled a key technology to achieve sustainable and reliable heating worldwide by the International Energy Agency. (IEA, 2022) However, mostly electric compression heat pumps (CHP) have been investigated and installed for heating applications, which use large amounts of electric energy and thus only can operate truly emission-free if the supplied electricity is produced by renewable energy sources. (IEA, 2023) SPAHPs utilise solar energy to power an AHP, which creates emission-free thermal energy that can be used for heating applications. (Wu et al., 2020, p. 26) While SPAHPs are commonly used in space cooling applications, the heating application has not received much attention as it holds major challenges such as unreliability, inapplicability and low heating performance under some circumstances. (Wu and Leung, 2020) To overcome these challenges different technologies have been developed, which are introduced and analysed in this review. Further, they are compared to each other, and it is found that the technology that is most capable of overcoming the introduced challenges is the advanced AHP-CHP parallel system.

3 Working principles

3.1 Absorption Heat Pump (AHP)

To understand the working principle and the challenges of the SPAHP it is crucial to understand the working principle of a conventional AHP. The most important feature of AHPs, in comparison to

CHPs, is that a mechanical compressor is not required in the AHP cycle. The latter utilises external thermal energy to separate a two-component solution, which comprises a high vapour pressure component (refrigerant, e.g. ammonia) and a low vapour pressure component (solvent, e.g. water) to increase heat. Figure 3-1 shows the schematics of an AHP for the purpose of supplying hot water. The devices in the grey box (generator, solution heat exchanger and absorber) are the replacement of what the compressor in the CHP would be. The rest of the devices, namely the condenser, evaporator and the valve are the same as those of a conventional CHP and pure refrigerant flows through them. (Grassi, 2018, p. 73)

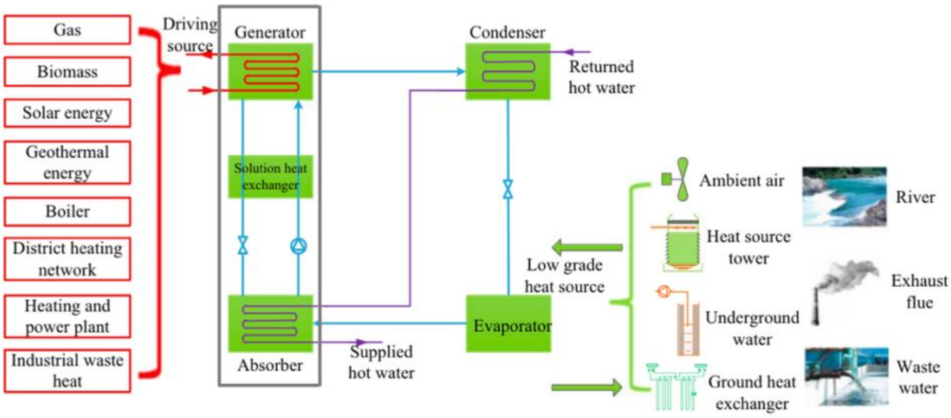

Figure 3-1 Schematic of an AHP (Modified from source: Wu et al., 2020, p. 26)

In the generator the solution is heated up externally by a thermal energy source (power source) that could be gas, biomass, geothermal energy, solar energy, etc. The refrigerant evaporates and goes to the condenser, where it is condensed and exchanges the phase-change heat with water. Next, the liquid refrigerant goes through the throttling valve where its pressure is reduced, and it changes to a two-phase refrigerant. The two-phase refrigerant arrives at the evaporator where it extracts energy from a low-temperature heat source such as the ambient air or the ground, which leads to the complete evaporation of the refrigerant. The refrigerant vapour travels to the absorber, where it is absorbed. (Wu et al., 2020, p. 26)
Apart from the refrigerant vapour, also the strong solution, which comes from the generator and is the part of the solution that did not evaporate to refrigerant vapour and hence has a strong ability to absorb vapour enters the absorber. The refrigerant vapour is absorbed by the strong solution, which creates absorption heat that is released to the water in the hot water cycle that was already heated in the condenser before. After the absorption process, the solution is cold and has a weak absorption ability. It is pumped through a heat exchanger, where it exchanges heat with the strong solution that travels to the absorber. Subsequently, the weak solution reaches the generator, where it is heated up again, and the cycle starts from the beginning. (Wu et al., 2020, p. 26)

To summarise, the water temperature is increased by the condenser and the absorber, and the apparatus utilises a high-grade heat source such as gas or solar energy and a low-grade heat source such as the ambient air to do so.

3.2 Generic Solar-Powered Absorption Heat Pump (SPAHP)

The SPAHP is an AHP that uses solar energy as the power source that supplies energy to the generator. (Wu et al., 2020, p. 26) To collect solar energy, a solar collector is required that heats up a liquid which is transported to the generator, where it heats up the two-component solution and thus powers the SPAHP. The liquid needs to be brought to high temperatures to power the generator. As the solar collector's efficiency decreases with high temperatures, the overall efficiency compared to direct solar heating is only increased due to the additional heat extraction from a low-grade heat source which is enabled by the AHP cycle. (Wu et al., 2020, p. 243) Different solar collector designs are available, with the parabolic-trough collector having the widest application domain. (Wu et al., 2018a) The overall SPAHP system efficiency is calculated by multiplying the solar collector efficiency with the coefficient of performance (COP) of the AHP (Wu et al., 2020, p. 244):

$$\eta_{SPAHP-system} = \eta_{SPAHP-collector} * COP_{AHP}$$

If the fluid heated in the solar collector is water, the solar collector needs to be emptied when it is not in operation to prevent freezing. Alternatively, salt solutions or oil can be utilised. (Wu et al., 2018a)

4 Challenges

The generic SPAHP suffers from four key challenges that prevent its wider application:

[1] **Unreliability caused by unstable solar energy supply.** The generic SPAHP cannot function properly without enough energy from solar radiation to power the generator. (Wu and Leung, 2020) The amount of solar radiation reaching the Earth's surface is dependent on the geographic location, the time, the season, the local landscape and the weather. (Office of Energy Efficiency & Renewable Energy, no date)

[2] **Decreased applicability due to insufficient solar energy resources.** Sufficient access to solar radiation must be given at the application site. Often, the space of the roof is not sufficient to install a standalone SPAHP system that meets the demand of the building, however, this space and the available solar energy resources must not remain unused. (Wu and Leung, 2020)

[3] **Low heating performance at low power source temperatures.** (Wu et al., 2020, p. 109) The power source temperature is the temperature of the hot fluid that is provided by the solar collector and is dependent on the solar radiation and the type of collector. (Wu et al., 2018a) Low heating efficiency and capacity at low power source temperatures is an especially important challenge, as the heating load typically is highest when the ambient temperature and the solar radiation are low.

[4] **Low heating performance at low ambient temperatures.** (Wu et al., 2020, p. 109) The ambient temperature is the temperature of the surrounding environment of the evaporator, which serves as the second heat source. (Wu et al., 2020, p. 26) Just like challenge 3, decreased efficiency and capacity at cold ambient temperatures is an especially important challenge, as heating demand typically is highest at low ambient temperatures with little available solar energy.

In conclusion, the application of SPAHPs is mainly limited by their unreliability caused by unstable solar energy supply, the low applicability caused by insufficient solar energy at site and the low heating performance at low energy source or ambient temperatures.

5 Technical Solutions

To overcome the challenges mentioned above and thus make the SPAHP more attractive for a wide range of applications, two different approaches can be followed: using improved working fluids and using advanced cycles. As the extent to which working fluids can increase the SPAHP performance is limited, the development of advanced SPAHP cycles is the more promising approach. (Wu et al., 2020, p. 109) Therefore, in the following different adapted SPAHP cycle designs that solve one, or multiple of the above-mentioned challenges are introduced, analysed, and compared to each other according to the degree to which they overcome the challenges. In the following challenges are considered overcome if: Challenge [1] unreliability: The heating system can provide heat without using solar energy; Challenge [2] inapplicability: The system can provide the entire heating demand even if not enough solar energy resources are available at site to meet the entire heating demand; Challenge [3] low performance at low power source temperatures: The required power source temperature and thus the amount of solar energy to power the AHP is reduced compared to the generic SPAHP and the heating performance increased under these circumstances; Challenge [4] low performance at low ambient temperatures: The SPAHP's performance at low ambient temperatures is increased compared to that of the generic SPAHP, assuming the power source conditions are the same.

5.1 Hybrid Energy Source System

In the hybrid system the SPAHP is coupled with another energy source. This can either be done indirectly, by introducing a separate heating device (Grassi, 2018, p. 257) or directly by using an additional energy source to power the AHP. (Dai et al., 2018)

5.1.1 Indirect Hybrid Energy Source System

In the indirect hybrid energy system, the SPAHP is combined with another, separate heating system such as a boiler. Figure 5-1 shows the schematic of an indirect hybrid energy source system that has three working modes: 1) boiler only mode; 2) boiler + heat pump mode; and 3) heat pump only mode. The boiler only mode is activated when the SPAHP is unable to provide hot water for the application's demand. In the boiler + heat pump mode the SPAHP provides hot water at the currently achievable temperature level which is too low for the application. The boiler compensates this shortcoming by supplying hotter water to adapt the total temperature of the water to the demands of the application. In the heat pump only mode the SPAHP achieves hot water temperatures that are sufficient for the application and the boiler is not activated. (Grassi, 2018, p. 157)

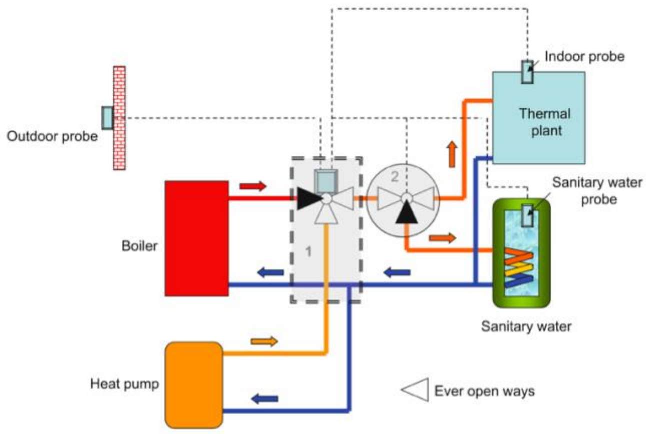

Figure 5-1 Schematic of indirect hybrid energy source system including a sanitary water reservoir (Source: Grassi, 2018, p. 158)

This system provides a solution to the unreliability and low applicability of the SPAHP. Depending on the type of boiler it can also be an emission-free solution. However, a second heating device needs to be implemented which increases the overall system complexity. Further, the challenge of low performance of SPAHPs at cold power source and low-grade heat source temperatures is not addressed by this approach, as the system would switch into boiler only mode under these circumstances.

5.1.2 Direct Hybrid Energy Source System

This approach combines thermal energy from solar radiation with thermal energy from another source such as gas to power the generator. Fig 5-2 shows the schematic of a solar and liquified petrol gas (LPG) powered AHP that uses a generator-absorber heat exchanger (GAX). This device has three working modes: 1) hybrid mode, where the LPG burner and the solar collector supply heat to the generator; 2) solar only mode, where only the solar collector provides the thermal energy for the generator; and 3) LPG only mode, where the LPG burner provides all the thermal energy for the generator. (Dai et al., 2018)

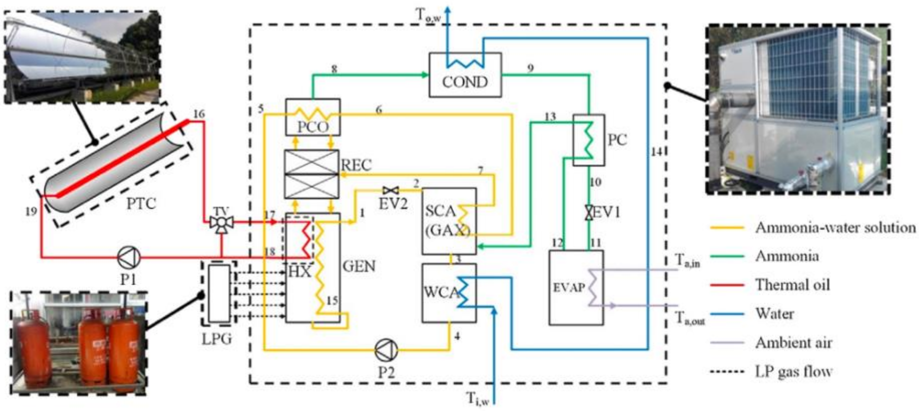

Figure 5-2 AHP driven by LPG and solar energy (Source: Dai et al., 2018)

This approach is effective in addressing the reliability and applicability issues due to the unstable solar energy supply and insufficient solar energy resources respectively, as the LPG burner can be used when the solar energy is insufficient to power the device. However, this approach does not increase the performance of the SPAHP at low power source temperatures or low ambient temperatures, as in this case the solar energy is exchanged for the additional power source. Moreover, the environmental benefits of the SPAHP are mitigated if fossil fuel based energy sources are utilised as emissions arise due to their combustion.

5.2 Combining AHP and CHP

The AHP-CHP hybrid system combines AHP and CHP. Based on the role of the AHP/CHP sub-systems the AHP-CHP hybrid systems can be categorised in four basic groups: [1] CHP-assisted AHP; [2] AHP-assisted CHP; [3] AHP-CHP cascade system; and [4] AHP-CHP parallel system. (Wu and Leung, 2020)
The AHP-assisted CHP enables highly efficient high temperature output, however, does not overcome the aforementioned challenges and is therefore not further discussed in this analysis. (Wu and Leung, 2020)

5.2.1 CHP-assisted AHP

The CHP-assisted AHP increases the heating capacity and efficiency at low power source temperature-levels (Wu et al., 2016a) and in cold ambient (Wu et al., 2016b). The dominant AHP sub-cycle is supported by an auxiliary CHP sub-cycle. The CHP sub-cycle compressor can be installed either in between the absorber and evaporator or alternatively between generator and condenser. Installation between the absorber and evaporator increases efficiency and capacity under low ambient temperature and low power source temperatures (Gao et al., 2019), which is especially advantageous for SPAHPs. The efficiency and capacity at low power source temperatures is increased due to the increased absorption pressure and subsequently a stronger solution entering the generator, which increases the refrigerant flow rate and thus the efficiency. (Wu et al., 2016a) The increased efficiency and capacity at low ambient temperatures is achieved by allowing for lower evaporation pressures and temperatures, while maintaining high absorption pressure, which increases the refrigerant concentration difference in the solution and thus increases the efficiency. (Wu et al., 2016b) Figure 5-3 show the schematic of such a device.

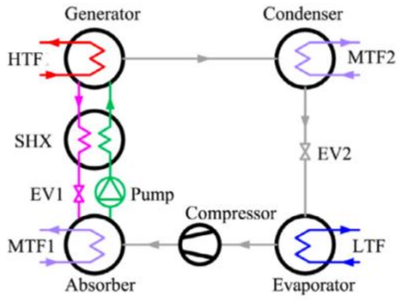

Figure 5-3 CHP-assisted AHP (Source: Gao et al., 2019)

While this adapted cycle provides a solution for the decreased heating performance in cold environments and at low power source temperatures, it does not increase the reliability, nor it solves the applicability problems due to insufficient solar energy supply of the SPAHP. (Wu and Leung, 2020)

5.2.2 AHP-CHP Cascade System

The AHP-CHP cascade system comprises a dominant AHP and a dominant CHP sub-cycle. By combining the AHP sub-cycle with the CHP sub-cycle cooling or subcooling of the CHP-condenser can be achieved, which increases the achievable temperature lift. The cooling configuration has superior efficiency at low ambient and high power source temperatures and is shown in Figure 5-4. (Wu and Leung, 2020)

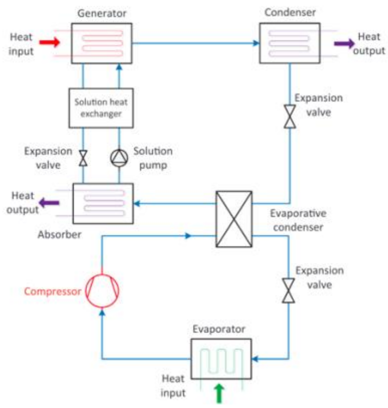

Figure 5-4 AHP-CHP cascade system (Source: Wu and Leung, 2020)

While this approach allows for increased heating performance at low ambient temperatures, it does not address the rest of the challenges, as its operation is dependent on the availability of a sufficient amount of solar energy to power the AHP sub-cycle. Thus, it fails to overcome the issue of unreliability caused by unstable solar energy supply, low heating performance due to low power source temperatures and low applicability caused by low solar energy resources at site.

5.2.3 AHP-CHP Parallel System

The AHP-CHP parallel system has two distinct configurations: internally parallel or externally parallel. The externally parallel configuration comprises a AHP and a CHP that are connected through an external water loop, while the AHP and CHP share the same refrigerant in the internally connected absorption-compression heat pump (shown in Figure 5-5). The internally parallel configuration is advantageous as it is more compact and fewer tubes and heat exchangers are needed. (Wu and Leung, 2020) The refrigerant flows through both sub-cycles and the ratio of refrigerant can be adjusted to account for various circumstances and to reach different capacities and efficiencies. If little solar energy is available, the amount of refrigerant going through the CHP sub-cycle may be increased to balance out the decreased heat supply by the AHP sub-cycle. In the extreme cases the refrigerant flows only through one sub-cycle, however, refrigerant flow through both sub-cycles simultaneously is potentially preferable in most cases. (Wu et al., 2018b)

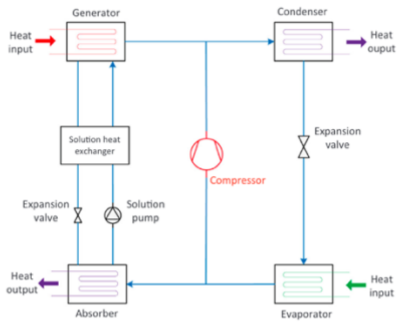

Figure 5-5 AHP-CHP parallel system (Source: Wu and Leung, 2020)

The AHP-CHP parallel system is a good approach to increase the applicability domain of SPAHPs as it overcomes the reliability and the applicability challenges. However, this approach does not provide a solution to increase SPAHP heating performance at low power source temperatures, as the refrigerant ratio going through the CHP sub-cycle may simply be increased if the solar energy supply is low. (Wu and Leung, 2020) Further, the performance at low ambient temperatures is not increased compared to the generic SPAHP.

5.2.4 Advanced AHP-CHP Parallel System

Wu and Leung (2020) introduced a novel approach to overcome the challenges of SPAHPs based on the AHP-CHP parallel system, where the CHP sub-cycle is composed of two compressors in series and the generator is connected to the pipe in between those compressors. Figure 5-6 shows the schematic of the proposed device. After exiting the evaporator, the refrigerant can follow two different paths: One going to the thermal compressor (AHP sub-cycle) and one going to the electric compressor (CHP sub-cycle). The refrigerant coming from the thermal compressor can be injected in the electric compressor where the refrigerant from both streams is compressed together. This configuration leads to lower compression pressure in the thermal compressor which allows its operation at lower power source temperatures, lower ambient temperatures and increased temperatures of the heat sink. (Wu and Leung, 2020)

The device has five operation modes which can be defined by the refrigerant ratio in the AHP and CHP sub-cycles and the injection pressure ratio (which is the pressure at injection port divided by the pressure at discharge port): [1] AHP-CHP parallel mode with refrigerant injection (valve 1 closed, valve 2 open): The refrigerant goes through both sub-cycles, and the portion of the refrigerant going through the thermal compressor is injected in the electric compressor. This mode can be used at low power source or low ambient temperatures, as it decreases the generation pressure. [2] AHP-CHP parallel mode without refrigerant injection (valve 1 open, valve 2 closed): The refrigerant goes

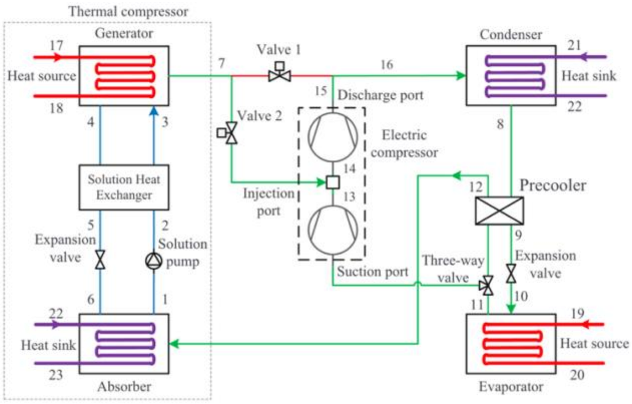

Figure 5-6Advanced AHP-CHP parallel system (Modified from source: Wu and Leung, 2020)

through both sub-cycles but the portion coming from the thermal compressor does not enter the electric compressor but goes to the condenser directly. This mode is activated at high power source temperatures or high ambient temperatures. [3] CHP-assisted AHP mode (valve 1 closed, valve 2 open): The compressor close to the suction port is deactivated, which basically creates a CHP-assisted AHP. This mode is used when the heating demand is achievable with the AHP sub-cycle alone, but the performance can be increased by an operating compressor after the generator. [4] AHP mode (valve 1 open, valve 2 closed): When the AHP alone can account for the necessary heating capacity and increased pressure would have a negative impact on the system's performance, the electric compressors are deactivated, and refrigerant only goes through the AHP sub-cycle, which essentially resembles the generic SPAHP. [5] CHP mode (valve 1 closed, valve 2 closed): With no power source energy available, the refrigerant goes through the CHP sub-cycle only, resembling an electric CHP.

This approach successfully overcomes all four major challenges stated above as it achieves increased heating performance at low power source and low ambient temperatures, overcomes the unreliability problems as it can be operated solely by the CHP sub-system, and increases the applicability at sites with little solar energy resources as it can account for the entire heating demand even with insufficient solar energy resources available at the installation site. (Wu and Leung, 2020)

5.3 Advanced AHP cycles

Advanced AHP cycles comprise the double-stage AHP and the coupled double-stage AHP. The first mentioned cycle achieves efficient use of cold environment temperatures by splitting the pressure lift process into two steps, while latter achieves higher efficiency at low ambient temperatures by splitting the temperature lift process in two steps. By splitting up the temperature or pressure lift process, the concentration difference in each step can be increased and thus the efficiency at low ambient temperatures. (Wu et al., 2020, pp. 109 - 112)

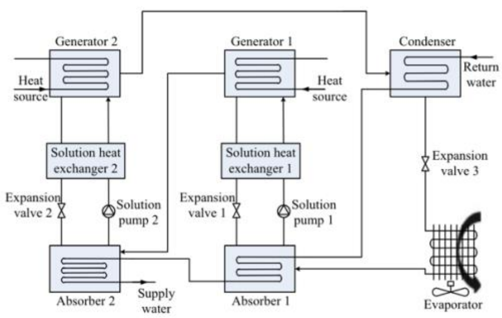

Figure 5-7 double-stage AHP (Source: Wu et al., 2020, p.112)

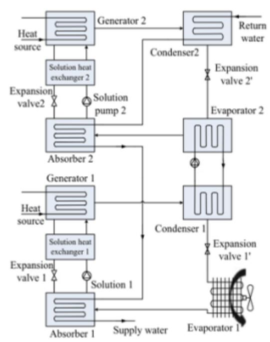

Figure 5-8 coupled double-stage AHP (Source: Wu et al., 2020, p.111)

Apart from the increased heating performance at cold ambient temperatures, the advanced AHP cycles do not solve any other of the indicated challenges.

6 Analysis and Comparison

When comparing the technologies to each other it is evident that the advanced AHP-CHP parallel system is the only introduced technology providing solutions to all four major challenges that prevent the wider application of SPAHPs. While the direct and indirect hybrid energy source system and the AHP-CHP parallel system provide solutions for the unreliability and inapplicability issues, they fail to increase the SPAHP heating performance at low power source and ambient temperatures. In contrast, the CHP-assisted AHP enables better heating performance using low power source and low ambient temperatures but fails to account for the unreliability and inapplicability of SPAHPs. The AHP-CHP cascade system and the advanced AHP cycles solely increase the heating performance at low ambient temperatures and fail to overcome any other of the challenges. Table 6-1 provides an overview on which technologies provide solutions for which challenges.

Technology	**Challenge**			
	[1]	[2]	[3]	[4]
	unreliability due to an unstable solar energy supply	low applicability caused by insufficient solar energy resources at the installation site	low heating performance at low power source temperatures	low heating performance at low ambient temperatures
Indirect Hybrid Energy Source System	√	√		
Direct Hybrid Energy Source System	√	√		
CHP-Assisted AHP			√	√
AHP-CHP Cascade System				√
AHP-CHP Parallel System	√	√		
Advanced AHP-CHP Parallel System	√	√	√	√
Advanced AHP Cycles				√

Table 6-1 Overview of technologies and their ability to overcome different challenges.

7 Conclusion

SPAHPs are a technology that can contribute to achieve global sustainable heating, by using solar energy. However, the generic SPAHP suffers from four major problems that prevent their wider application: unreliability due to an unstable solar energy supply, low applicability caused by insufficient solar energy resources at the installation site, low heating performance at low power source temperatures and low performance at low ambient temperatures. In this report seven adapted SPAHP cycles are introduced, and it is analysed to what extent they are successful in overcoming the identified challenges and thus expand the applicability domain of SPAHPs. It is found that the advanced AHP-CHP parallel system proposed by Wu and Leung (2020) is the only technology that can overcome all challenges, which makes it the best suited technology to increase the applicability domain of SPAHPs introduced and analysed in this review. The indirect and direct hybrid energy source system as well as the AHP-CHP parallel system can overcome the unreliability and inapplicability challenges arising from unstable and insufficient solar energy supply; however, they do not increase the SPAHP heating performance when little solar energy is available or at low ambient temperatures. The CHP-assisted AHP can increase the heating performance at low power source temperatures and low ambient temperatures but fails to overcome the unreliability and inapplicability issues. The AHP-CHP cascade system and the advanced AHP cycles only improve the performance in cold ambient.

8 References

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