Prospects of heat pump for thermal energy decarbonization

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Thermal energy occupies half of the global end-user energy consumption, and is related to 90% of the energy consumption.[1] The decarbonization of thermal energy is crucial for controlling the global temperature. Heat pump could utilize renewable power to produce thermal energy efficiently, by utilizing low-temperature heat sources. This makes heat pump a key technology for thermal energy decarbonization. Currently, the total capacity of heat pump exceeds 1000 GW, meeting 10% of the global heating demand in buildings. This capacity will be further increased to 2100-2600 GW in 2030.[2] Except for its wide application in domestic heating, the role of heat pump is also changing.

With the development of high-temperature heat pumps, the application of heat pump is broadening to industry and other sectors. It is estimated that the providing thermal energy below 150°C with renewable energy powered heat pump could reduce ~20% of the entire carbon emission.[3] Higher output temperature of heat pump brings advantages, but also challenges. As shown in Eqs (1) and (2), the ideal COP (coefficient of performance) of heat pump driven by either electricity ($COP_{ele,ideal}$) or thermal energy ($COP_{heat,ideal}$) is decided by the temperature lift between output and input (T_{out}-T_{in}). With higher output temperature and larger temperature lift, the COP of heat pump drops rapidly. It is necessary to discuss in what scenarios should heat pump be focused on.

$$COP_{ele,ideal} = \frac{T_{out}}{T_{out} - T_{in}} \quad (1)$$

$$COP_{heat,ideal} = \frac{T_{out}}{T_{source}} + \frac{T_{source} - T_{out}}{T_{source}} \frac{T_{out}}{T_{out} - T_{in}} \quad (2)$$

EFFICIENT AND ELECTRIFIED HEAT SUPPLY

In traditional energy system, thermal energy is typically provided by the burning of fossil fuels. This will be gradually replaced by sustainable power, and electrification of thermal energy generation will be the alternative. To find the better option among electrical heating and heat pump heating, the competition between two pathways should be considered in different scenarios. Here, three scenarios are discussed including distributed domestic heating, centralized domestic heating and centralized industrial heating in Figure 1, considering their heavy heating demand.

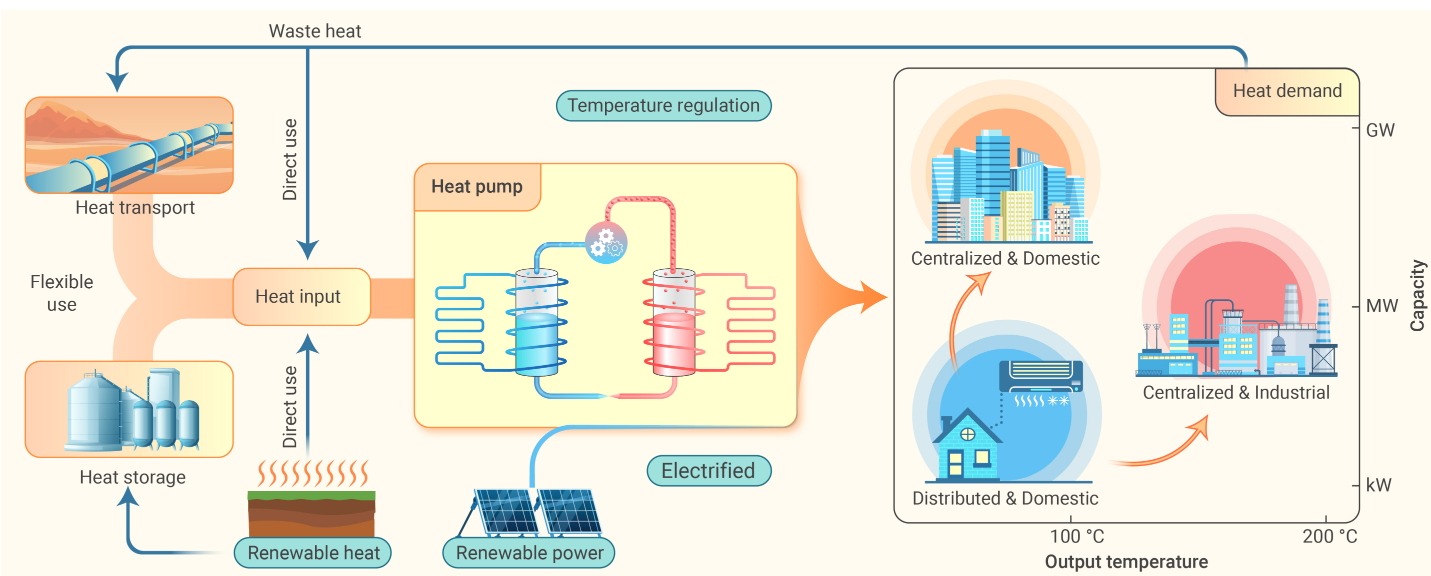

Figure 1. Roles of heat pump in thermal energy decarbonization including electrified heat supply and temperature regulation. Driven by renewable power, heat pump could achieve the efficient and electrified heat supply, which is developing from distributed heat supply for building to centralized heating for industry and building. Flexible use of the waste heat and renewable heat could be achieved by integrating heat pump into heat storage and heat transport, tacking the temperature, temporal and spatial mismatches simultaneously.

In distributed heating for building, the major consideration is the temperature of air as heat source. When the averaged ambient temperature is lower, the annual heating demand increases but the COP of heat pump decreases, which have opposite effects on the payback period of heat pump heating. In this case, the advantage of heat pump diminishes rapidly. However, if the cooling demand is considered in temperate zone, the combined heating and cooling supply with one heat pump unit will be the best choice, while the electrical heating needs to be combined with additional air-conditioner. This is promising for 2.6 billion people, living in regions with both heating and cooling demands.[2]

In centralized heating for industry, several differences exist comparing with distributed domestic heating. As the heating temperature in industry is much higher than that in distributed domestic heating, the COP of heat pump will be reduced and closer to electrical heating. If second-law efficiency of 30% is considered for heat pump, the heat pump becomes less efficient than electrical heating when temperature lift exceeds 130 °C. However, there are also two positive aspects. First, industrial heating could work much longer in one year. Process industry could work 8000 hours per year, which is 2.2 times longer than the domestic heating with 5 months.[4] This results in better energy-saving and other related benefits. Second, industrial waste heat could be recovered as heat input, with higher temperature than air. This not only saves energy input, but also reduces water consumption for cooling.[4]

Comparing with the other two scenarios, heat pumps is less considered for centralized heating in building. In cold regions, centralized heating is a basis for living, and consumes large amount of fossil fuels. When the use of fossil fuel is limited, finding new heat sources is essential, which could be biomass, nuclear, electrical heating or heat pump. Among these candidates, heat pump consumes less primary energy, but finding low-temperature heat sources for heat pump is challenging, considering the ultra-high power capacity in centralized heating. Industrial waste heat is the best option, but faces spatial mismatch between the waste heat source and heat pump unit. Collecting the waste heat with a low-temperature heat network could be one necessary approach.

Except for the different technical challenges, the energy saving and related benefits of heat pump also vary. According to the China Energy Conservation Association, heat pump could obtain COPs of 2.5, 2.32 and 2.78, under distributed domestic heating with -20~-12°C ambient temperature, centralized industrial heating with 150°C output temperature and centralized building heating with 110°C output temperature, respectively. Since industrial application has longer operation period, payback periods of 4.0, 1.2 and 3.6 years could be expected in the three scenarios respectively, considering the replacement for electrical boiler.

TEMPERATURE REGULATION OF THERMAL ENERGY

Except for the efficient heat supply of heat pump, one other important feature of heat pump is the temperature regulation. This is crucial for the flexible utilization of thermal energy, when considering the passive heat transfer from high temperature to low temperature. It is important not only in the waste heat recovery, but also in the storage and transportation of thermal energy, as shown in Figure 1.

In the temperature regulation of waste heat, both electrical heat pump and thermally-driven heat pump have been widely used. By consuming electricity or high-temperature thermal energy, low-temperature waste heat could be recovered and elevated to higher temperature, which could then be used for district heating, process preheating, drying and other scenarios. The energy, environmental and economic benefits of heat pump in waste heat recovery have been demonstrated, but its wide application is still limited by the temperature, temporal and spatial mismatches between waste heat and heating demand. Temperature mismatch could be partially solved by the high-temperature heat pump discussed by previous section, while the temporal and spatial mismatches need to be solved with heat storage and transportation.

Heat storage has been regarded as another key technology for the decarbonization of thermal energy, since the instability widely exists in the use of renewable energy and waste heat. Except for the thermochemical heat storage under laboratory investigation, the sensible and latent heat storage have been widely used. Although there exists plenty of choices for the heat storage medium, the working temperature, storage density, cost and safety of the heat storage medium need to be considered simultaneously for each specific application. For instance, the heat storage temperature must be lower than the heat source temperature and higher than the heat demand temperature. This strongly limits the choices the low-cost and high-density heat storage medium. If the heat pump is used in the charging or discharging processes for temperature regulation, the strong coupling between heat storage temperature and heat source/demand temperatures could be eliminated, enabling the flexible choice of heat storage medium and improved economic performance.

Compared with heat storage, heat transportation earns less attention due to two aspects. First, the heat transportation typically works with pipelines, with high initial investment. Second, the transportation of heat is accompanied with heat loss, which limits its transportation distance. For instance, the district heating network with hot water is typically limited within 50 km, and heat transportation with steam is even shorter. In recent years, the temperature difference of heat transportation with hot water has been significantly enlarged by absorption heat pump, promoting the transportation distance up to over 200 km.[5] If this is further combined with sorption cooling or high-temperature heat pump, the cooling demand and industrial heating demand could also be supplied, prolonging the operation duration and improving the economic performance. Considering the unique advantage of utilizing the "free" low-temperature heat in heat transportation, such flexible heat transportation with temperature regulation could be competitive in both energy-saving and economic aspects.

With heat storage and heat transportation as the heat sources, the heat pump could be more efficient and cover more scenarios. For instance, heat pumps with output temperature of 120 °C have COP of 2.2-2.8, when recovering waste heat with temperature of 50°C. If the heat source temperature is increased to 90°C with solar thermal storage or waste heat transportation, the COP could be increased to 5.7-6.5. This is crucial to increase the penetration ratio of heat pump, and 1% penetration of heat pump in China represents 2.3 $MtCO_2$eq of emission reduction.[3]

SUMMARY AND OUTLOOK

Targeting at the decarbonization of thermal energy, we provide perspectives of heat pump, including electrified heat supply and temperature regulation of thermal energy. In general, heat pump has played important roles in the distributed domestic heating, and is being promoted for industrial application. However, it is less considered for centralized district heating. For the application of heat pump in these three scenarios and beyond, the performance of heat pump is strongly related to both the heat source and output temperatures, which is not a concern for fossil fuel or electrical heating. To improve the overall performance of heat pump in these scenarios, spatial and temporal analyses for heat source and heat demand are necessary. As for the temperature regulation, heat pump has been used in temperature increase of waste heat or renewable heat, and its further integration with heat storage and transportation is expected.

This highlights the opportunities of heat pump in centralized heating for building with low-temperature heat network, heat pump integration in heat storage for flexible temperature match, and heat pump assisted heat transportation beyond domestic heating. Considering the long lifetime of fossil fuel boilers, the chances to replace them are limited in the coming decades. Policies on adopting heat pump for heating demand is urgent to be promoted together with the technical advances.

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DECLARATION OF INTERESTS

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