Flexible Heat Pump Cycle: Working Principle, Thermodynamic Essence, and Applications

Professor Zhibin Yu

Chair of Energy Engineering

Head of Energy Research Cluster

Royal Society Industrial Fellow (2023-2027)

The School of Engineering

The University of Liverpool

UNIVERSITY OF LIVERPOOL

Outline

- Background
- The working principle of the flexible heat pump (HP) cycle
- The thermodynamic essence of the flexible HP cycle
- The application of the flexible HP cycle

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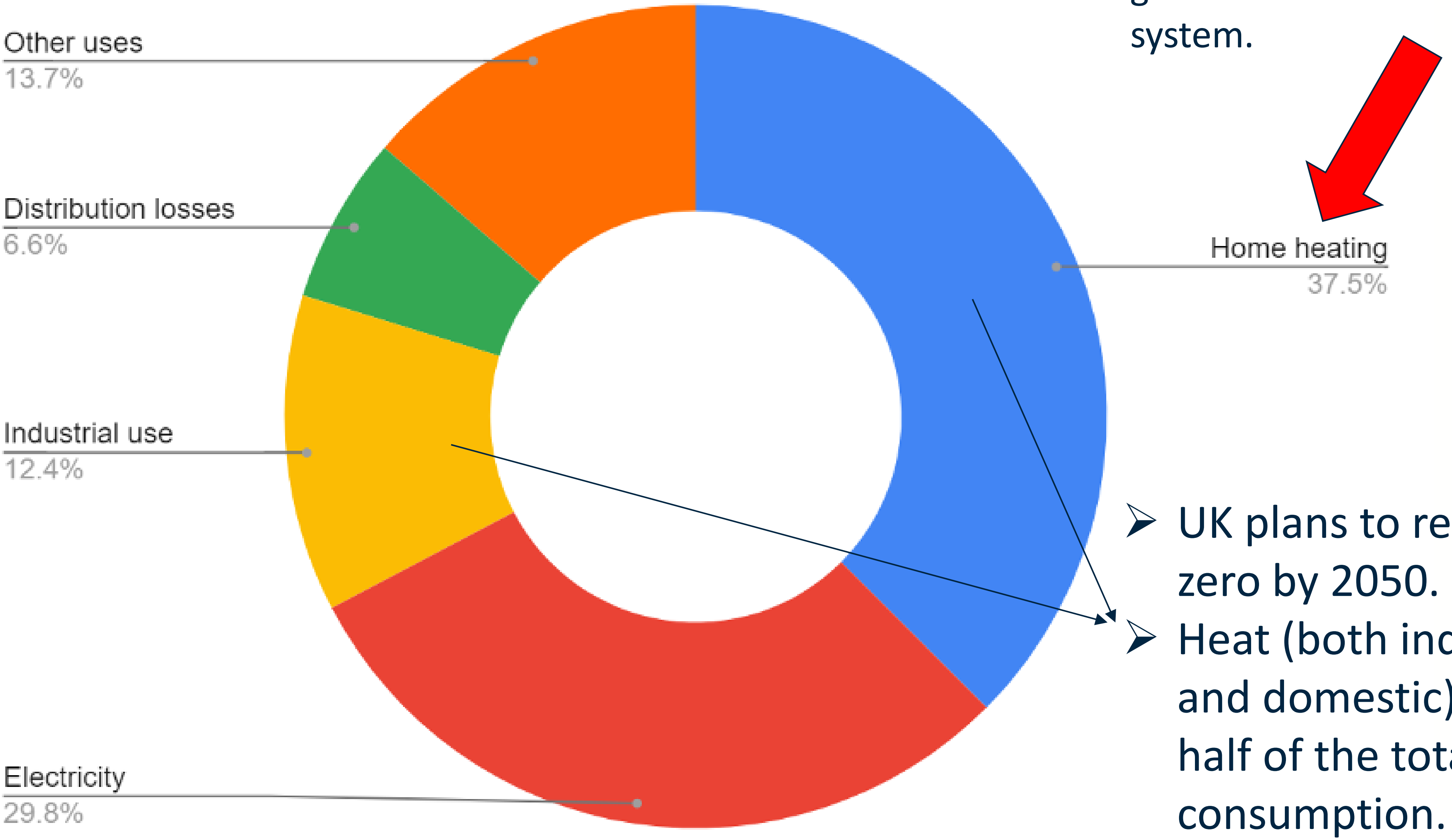
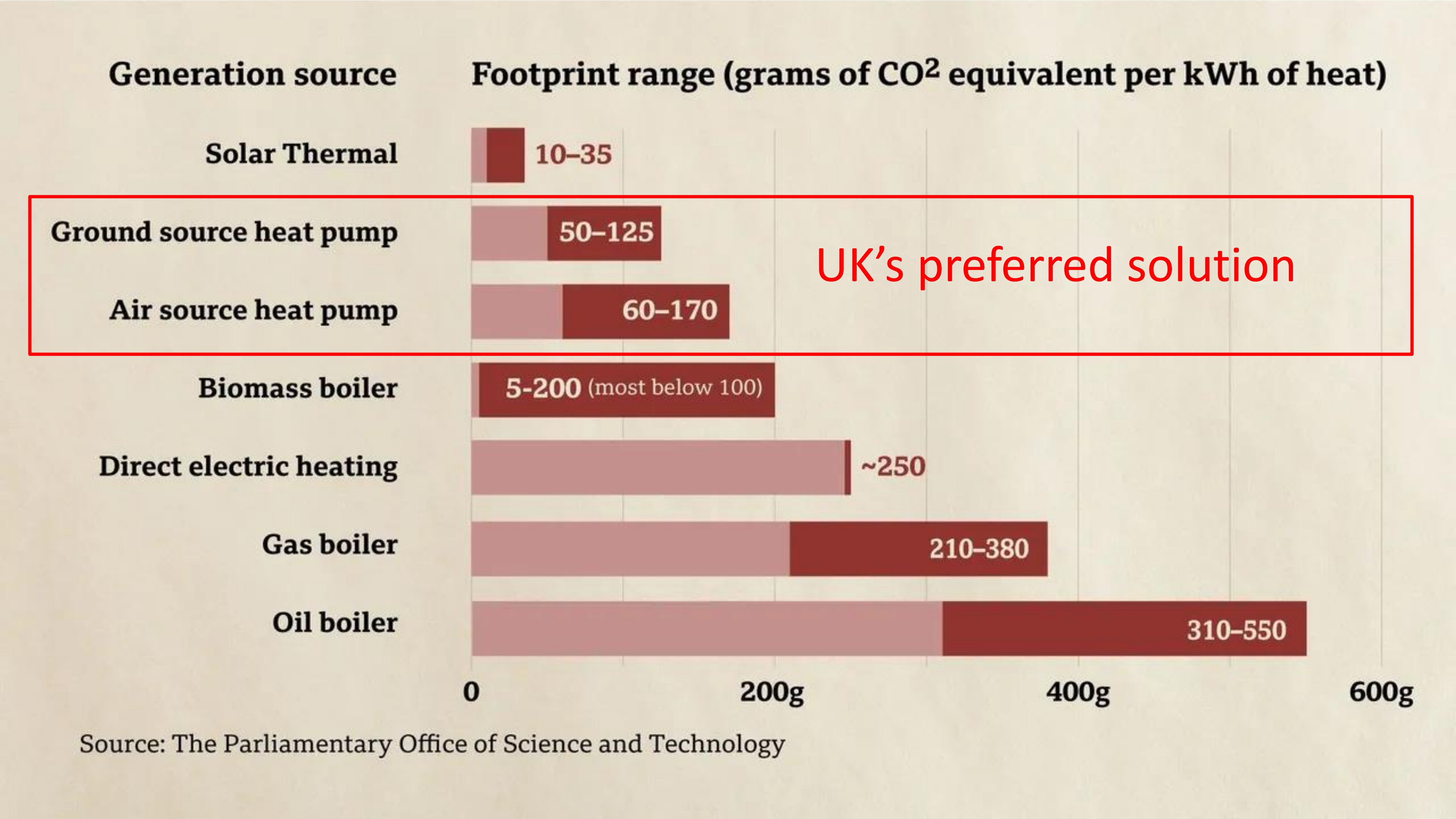
How the UK used gas in 2021. Source: BEIS, UK Energy Flow Chart for 2021

Over 80% of UK houses using gas boiler central heating system.



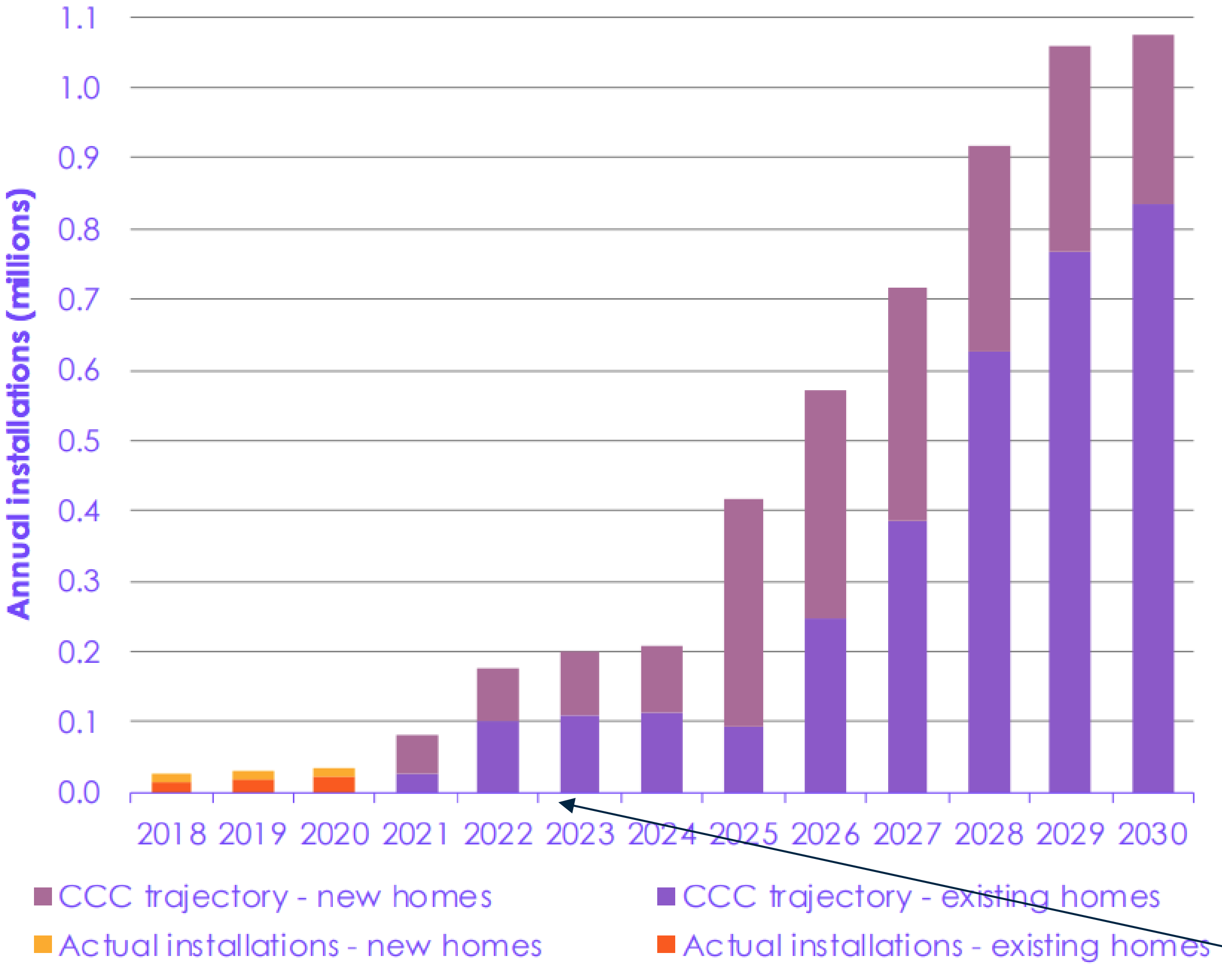
- UK plans to reach net zero by 2050.
- Heat (both industrial and domestic) is nearly half of the total energy consumption.

Carbon emissions of different heating technologies



https://www.bbc.com/future/article/20201116-climate-change-how-to-cut-the-carbon-emissions-from-heating

Heat pump installation rates in homes set against the Climate Change Committee's (CCC) net-zero "balanced pathway". Source: CCC.



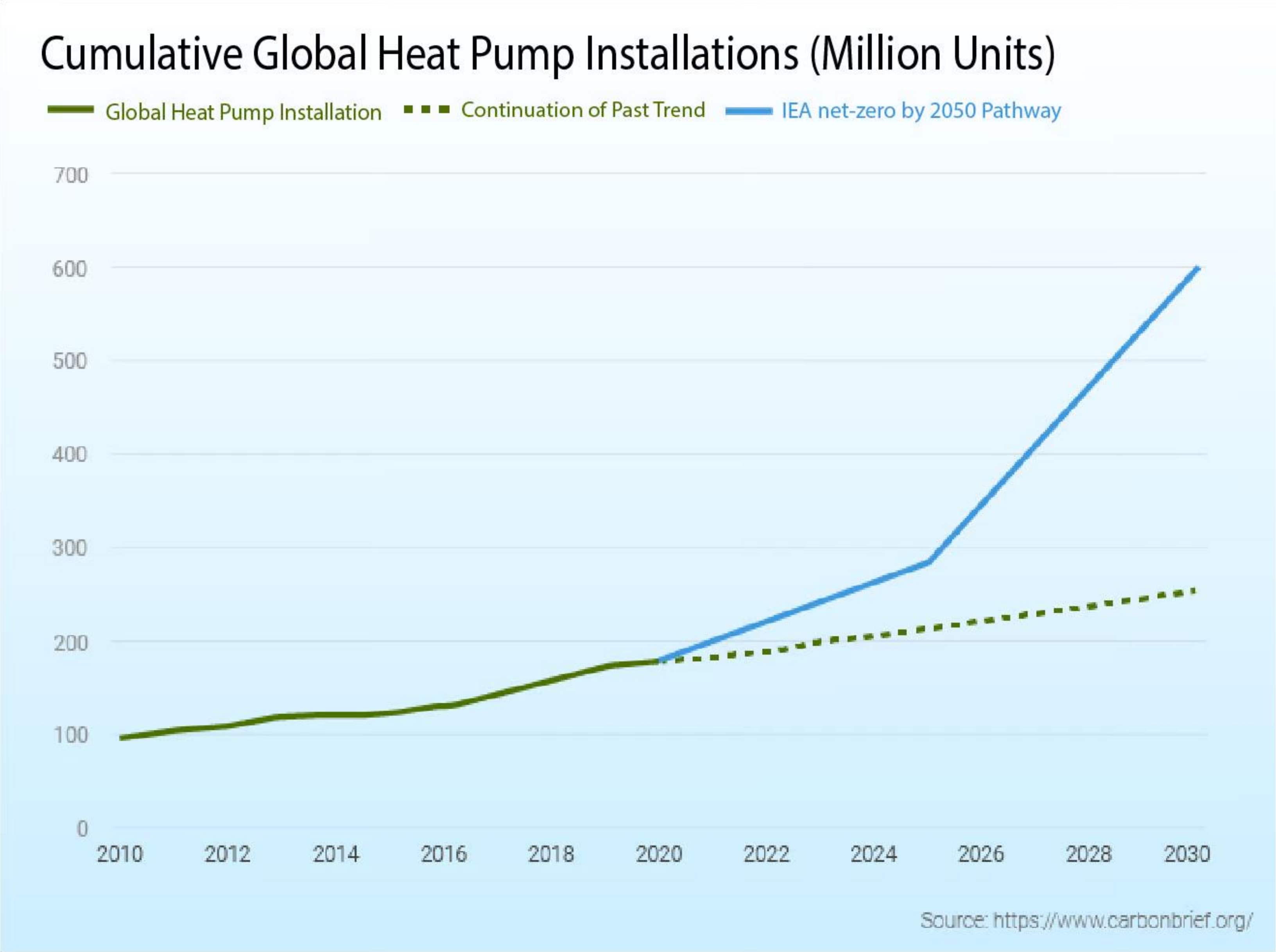
- UK government aims to install 19 million heat pumps to decarbonise domestic heating sector by 2050.
- The Government has set out its ambition to support the growth of the heat pump market to around 600,000 installation per year by 2028.
- A total of 55,000 heat pumps were installed in the UK last year.
- **The uptake of heat pump in the UK is very low!**

https://www.carbonbrief.org/in-depth-qa-how-will-the-uks-heat-and-buildings-strategy-help-achieve-net-zero/

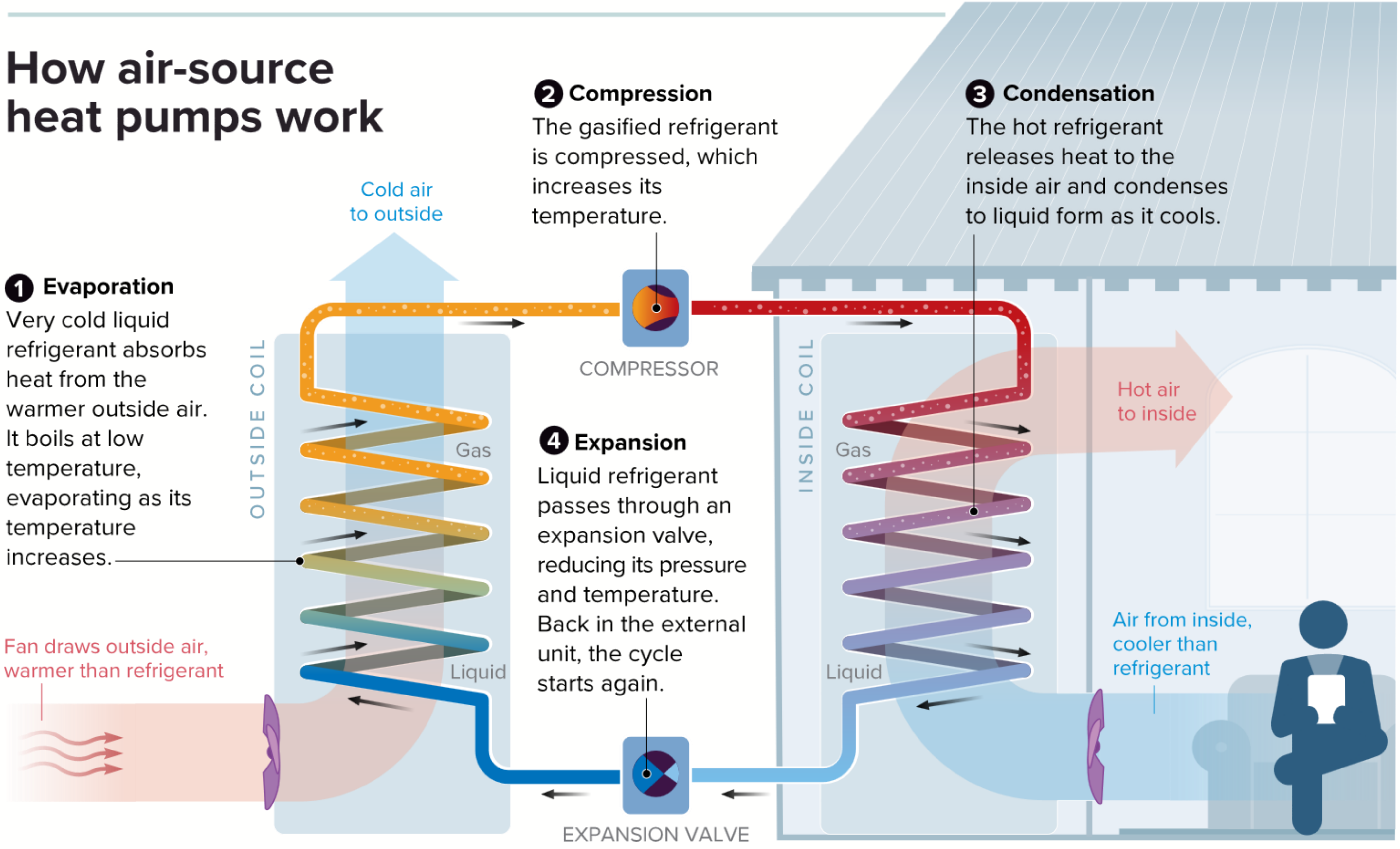
https://institutions.newscientist.com/article/2328095-uks-slow-heat-pump-efforts-will-take-600-years-to-meet-2050-target/#:~:text=The%20UK%20had%20the%20worst,in%20the%20UK%20across%202021.

Global heat pump installations projection

- Net Zero Emissions by 2050 Scenario (NZE Scenario).
- The number of heat pumps installed globally rises from 180 million in 2020 to around 600 million in 2030.



How air-source heat pumps work

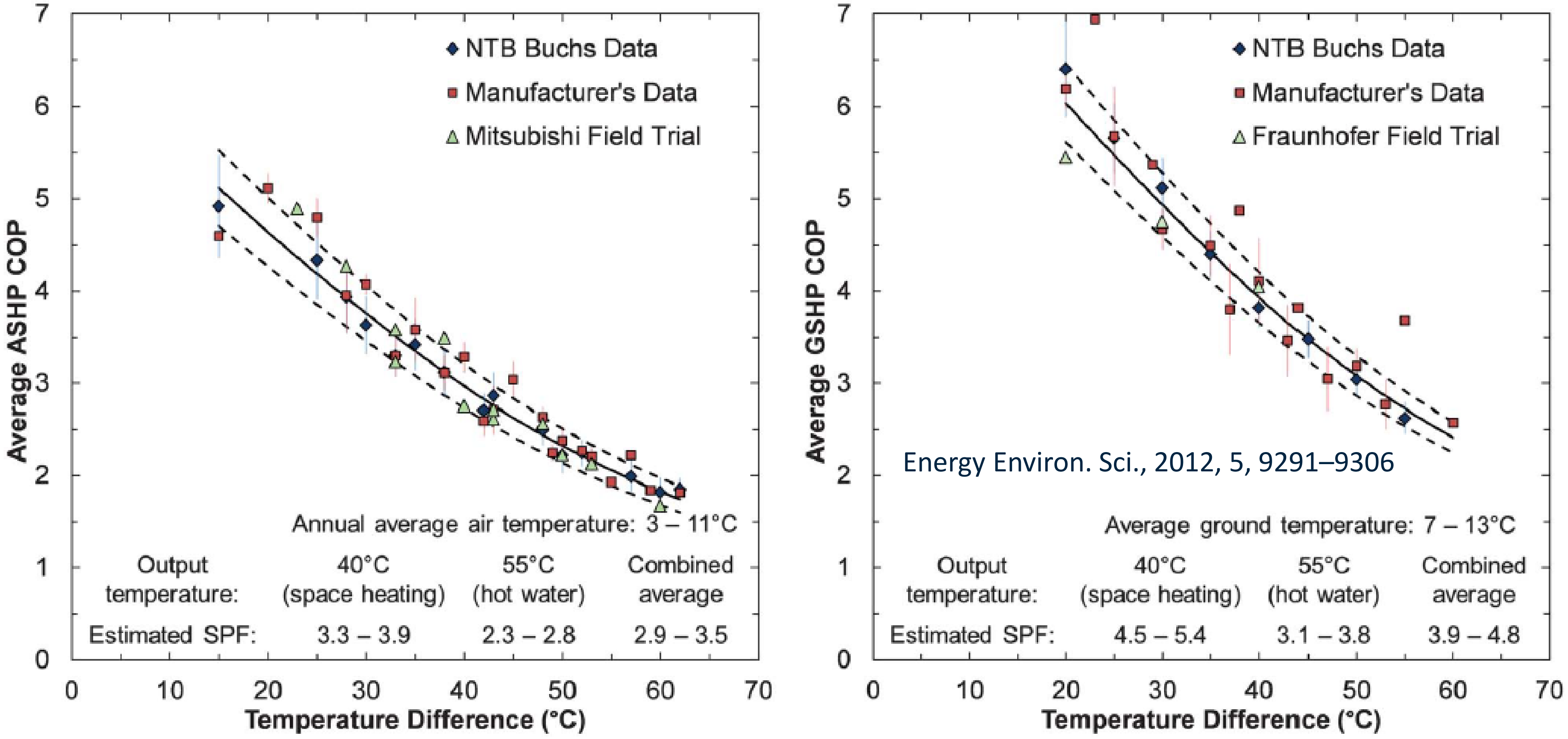


SOURCE: REPORTING BY C. BARANIUK

5W INFOGRAPHIC / KNOWABLE

Challenges (UK as case study):

- The central heating systems in UK houses are designed for high temperature supply,
- but most heat pumps in the markets are single stage with a heat supply temperature around 45 C,
- there is a mismatch between technology supply and demand.

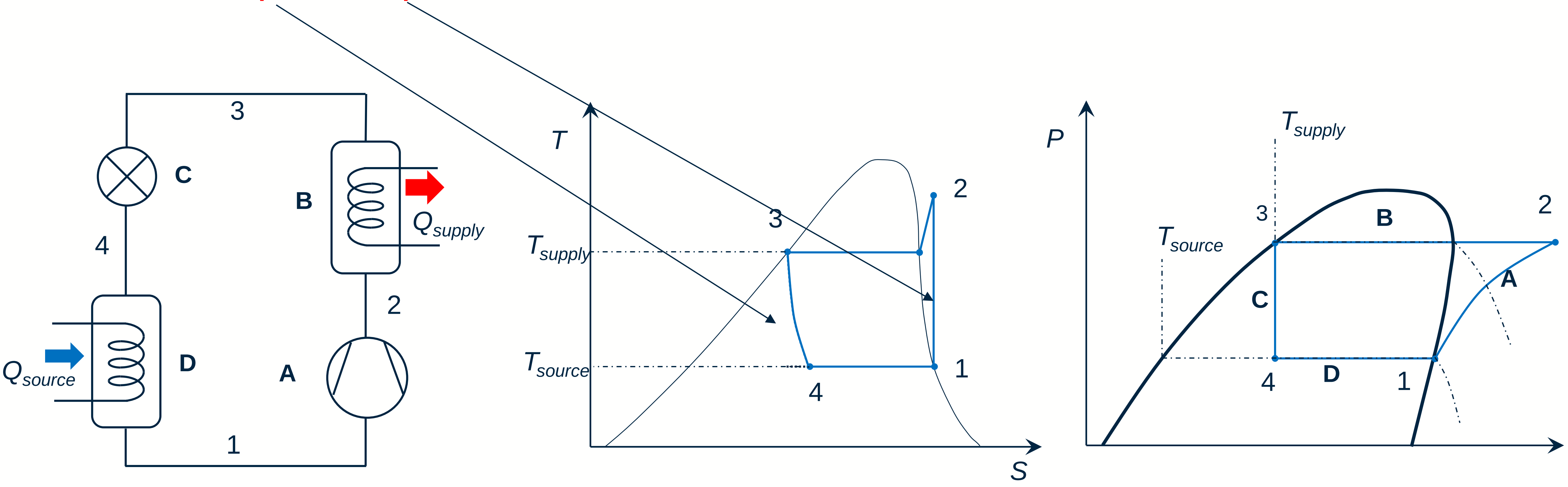


Energy Environ. Sci., 2012, 5, 9291–9306

How to further improve heat pump's energy performance, and ultimately the cost effectiveness !

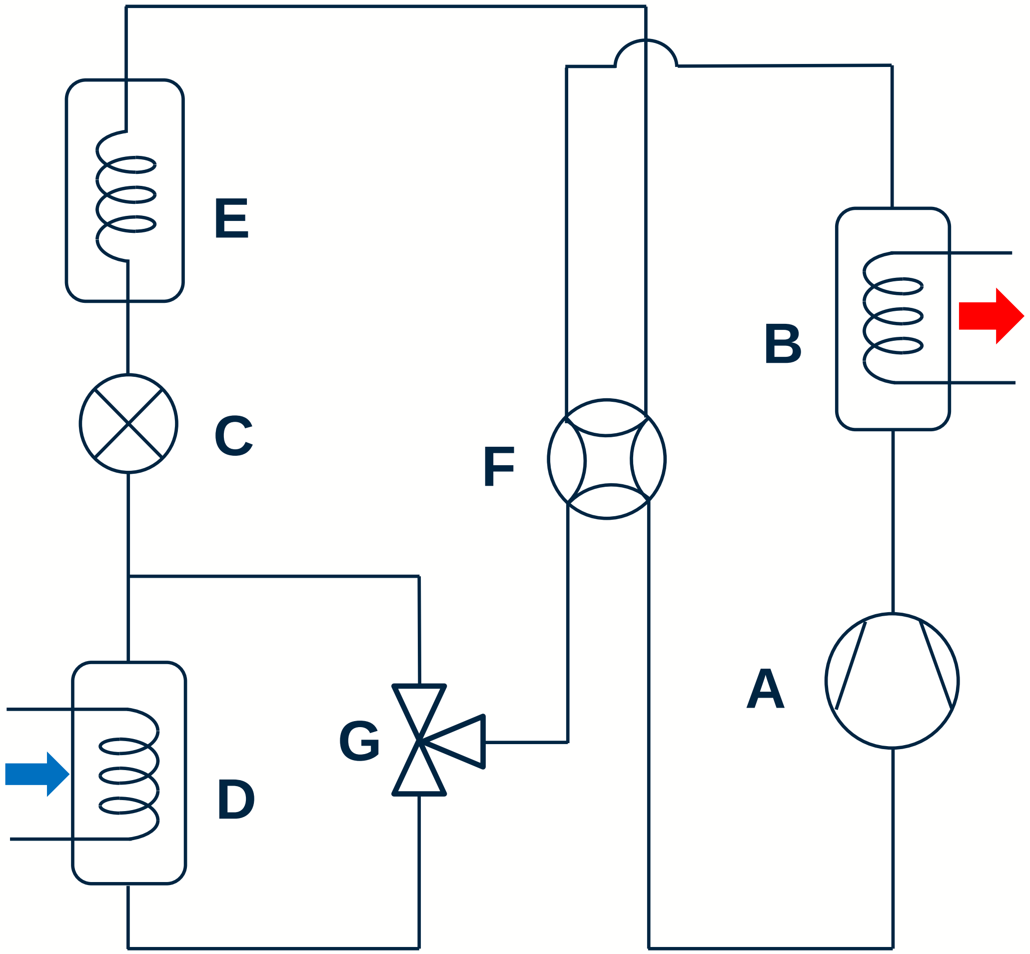
Evans-Perkins cycle and its issues for heat pump

- ❖ Thermal energy (i.e., sub-cooling heat) carried by the hot liquid refrigerant from the condenser is degraded during expansion process ‘3-4’, and then upgraded during compression process ‘1-2’.
- ❖ Such <u>degrade</u>/<u>upgrade</u> (in other words, recompression of flash gases) processes waste compressor power.



(a) (b) (c)

Flexible Heat Pump Cycle - a new method for COP improvement



A Compressor

B Condenser

C Expansion valve

D Evaporator

E Heat storage

F Four-way valve

G Three-way valve

The flexible heat pump integrates a thermal storage within a standard heat pump cycle to recover thermal energy for a wide range of applications to reduce power consumption.

*Yu, Z., McKeown, A., Hajabdollahi Ouderji, Z. et al. A flexible heat pump cycle for heat recovery. Commun Eng **1**, 17 (2022)*

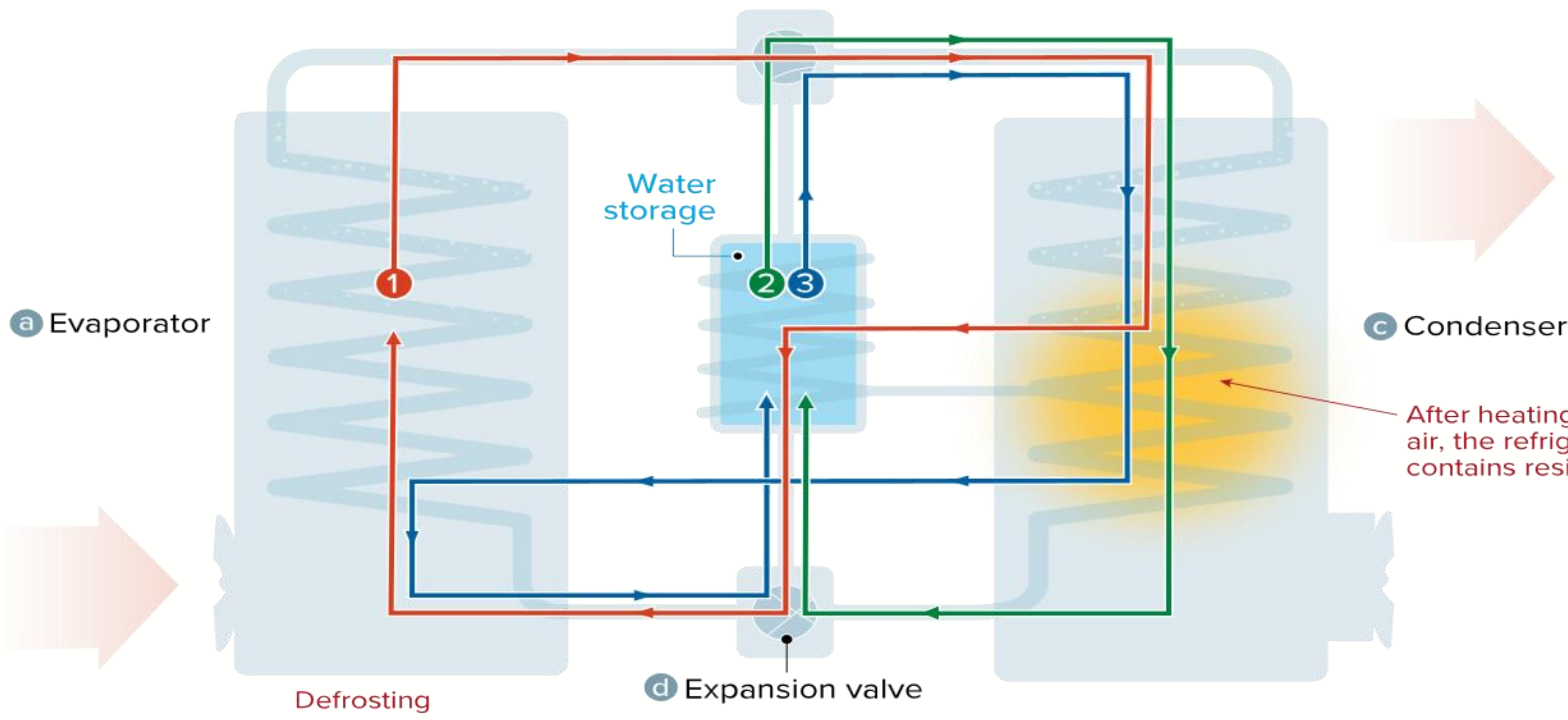
How a flexible heat pump works

A flexible pump uses the same components as a conventional pump (a b c d) but adds a water tank or other heat storage to recover and utilize the otherwise wasted heat that remains in the refrigerant after it supplies heat to the system.

1 Conventional mode (charging): Operates like a traditional heat pump, except that after heating the building, the refrigerant's residual heat is transferred to water storage.

2 Discharge mode: Instead of drawing heat from the outside, the system reclaims heat from the water storage to heat the house, skipping the evaporator.

3 Defrost mode: The system uses heat from the water storage to defrost the evaporator when required.



SOURCE: REPORTING BY C. BARANIUK

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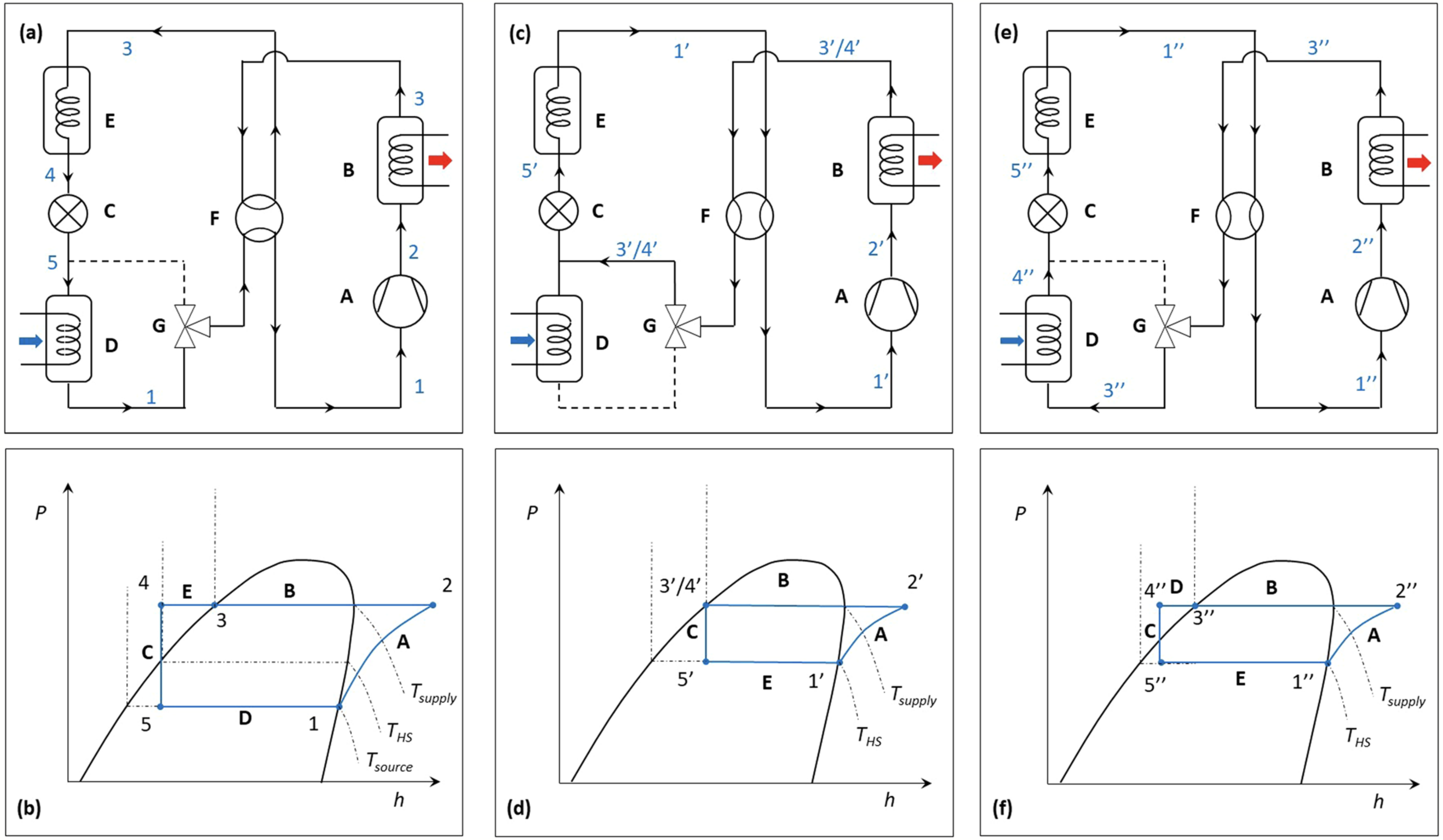
https://knowablemagazine.org/article/technology/2023/heat-pumps-becoming-technology-future

How the flexible heat pump cycle works

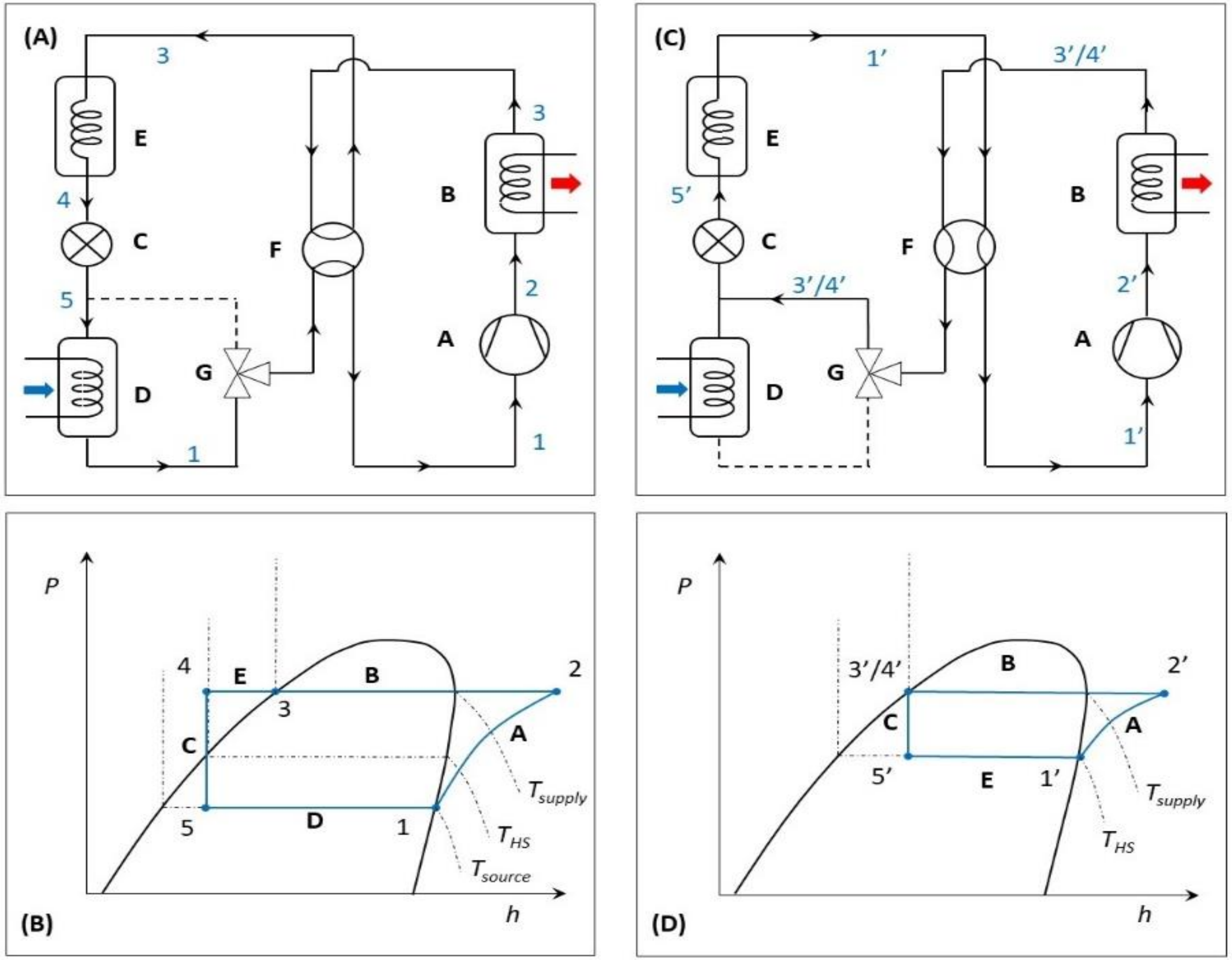
Charging (same as conventional HP) | Discharging (higher COP) | Discharging + Defrosting (higher COP)



Yu, Z., McKeown, A., Hajabdollahi Ouderji, Z. et al. A flexible heat pump cycle for heat recovery. Commun Eng ***1****, 17 (2022)*

Example application: Quasi-two-stage operation for compressor power reduction

- The recovery and storage of heat above heat source temperature allows the flexible heat pump to operate with a reduced power consumption (i.e., higher COP).
- In theory, up to 20% more efficient than current conventional single stage heat pumps.



Charging mode

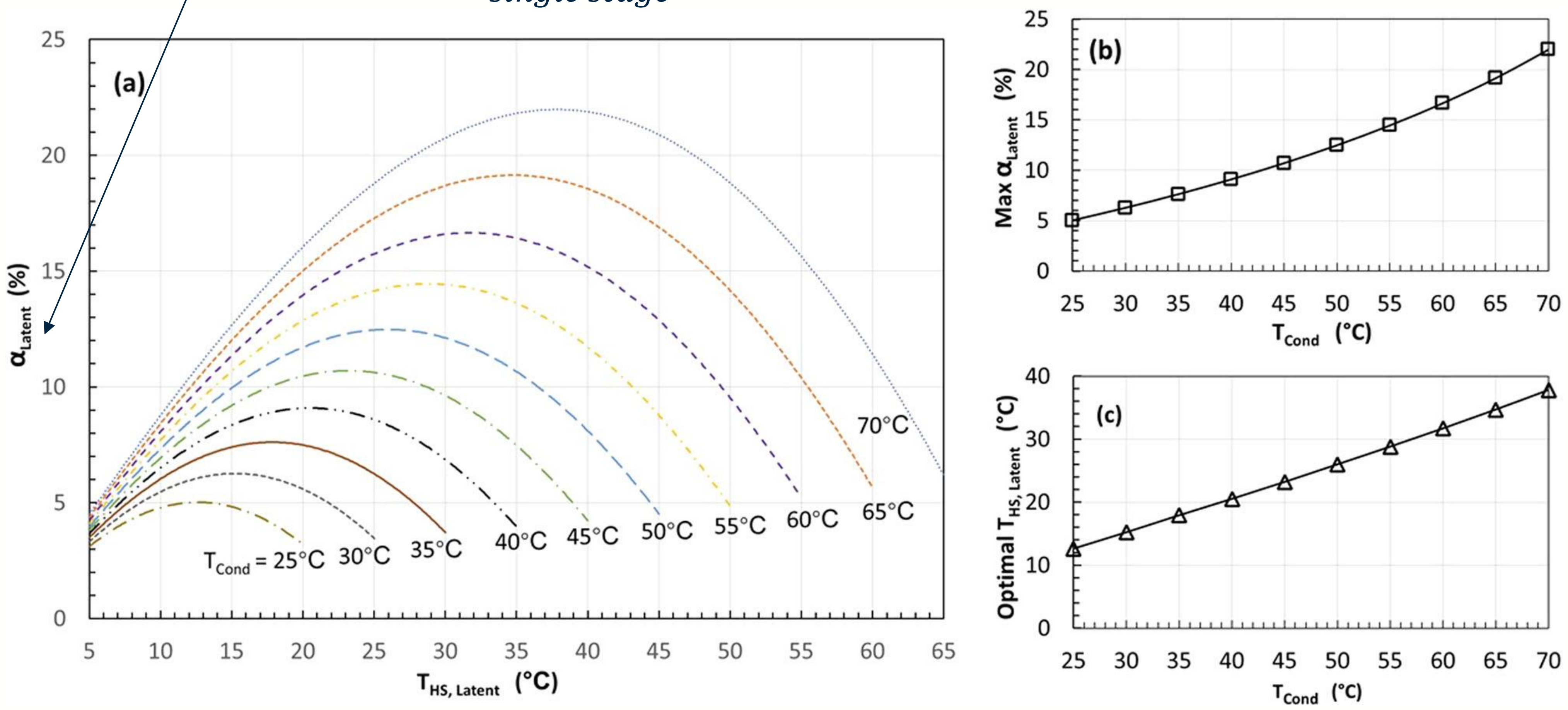
Discharging mode

Yu, Z., McKeown, A., Hajabdollahi Ouderji, Z. et al. A flexible heat pump cycle for heat recovery. Commun Eng ***1****, 17 (2022)*

COP improvement compared with single stage heat pump

Flexible heat pump cycle Quasi-two-stage operation (Latent heat storage)

$$\alpha = \frac{\overline{COP}_{Flexible\ HP} - COP_{single\ stage}}{COP_{single\ stage}} \times 100\%$$

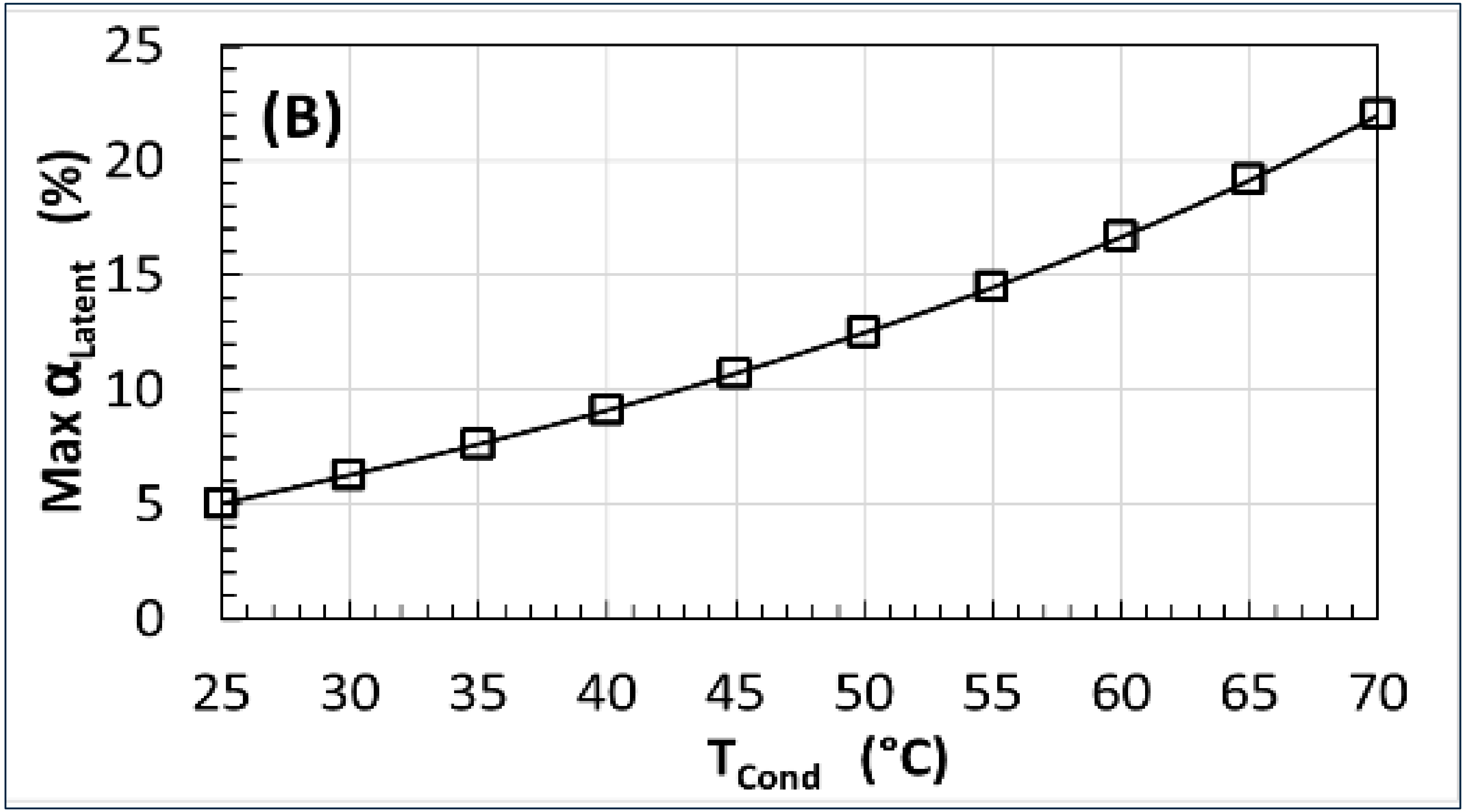


Yu, Z., McKeown, A., Hajabdollahi Ouderji, Z. et al. A flexible heat pump cycle for heat recovery. Commun Eng ***1****, 17 (2022)*

COP improvement compared with current technology

$$\alpha = \frac{\overline{COP}_{Flexible\ HP} - COP_{single\ stage}}{COP_{single\ stage}} \times 100\%$$

- Refrigerant: R134a
- Latent heat storage (e.g., phase change material)
- Heat source at 0 ℃
- Heat supply temperature varies from 25 to 70 ℃.
- COP improvement increases as supply temperature increases



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Impact of refrigerants

- Discharging mode has higher COP.
- More time on the discharging mode is more beneficial.
- β is the operating time ratio between discharging mode and changing mode.
- The higher the β, the higher the COP improvement.

$$\beta = \frac{\Delta t_{\text{discharge}}}{\Delta t_{\text{charge}}}$$

$$\beta_{\text{Latent}} = \frac{\Delta t_{\text{discharge}}}{\Delta t_{\text{charge}}} = \frac{\dot{m}_{r}(h_3 - h_4)}{\dot{m}_{r'}(h_{1'} - h_{5'})}$$

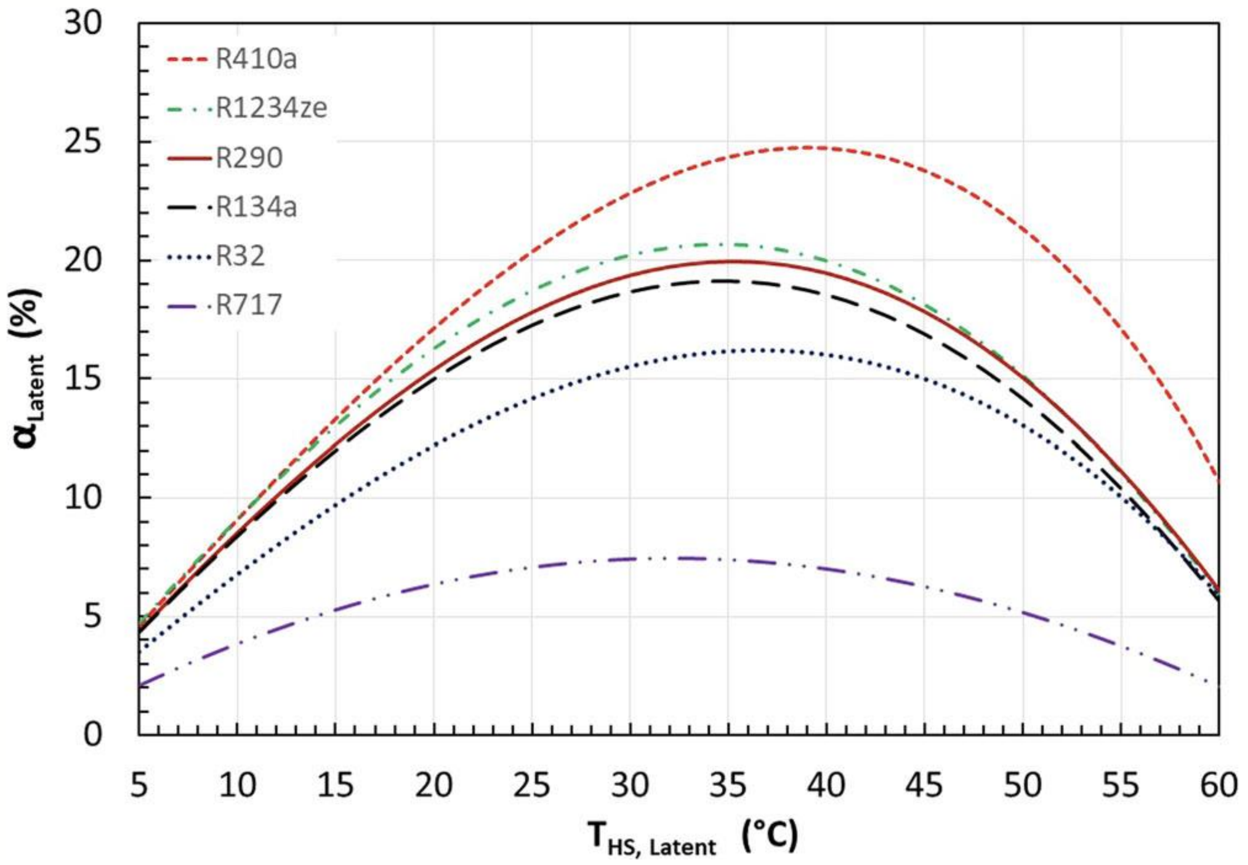

Table 1 The ratio of operational time between discharging and charging modes for the six selected refrigerants.

Refrigerant	R410a	R1234ze	R290	R134a	R32	R717
β_{Latent}	0.46	0.40	0.39	0.38	0.31	0.15

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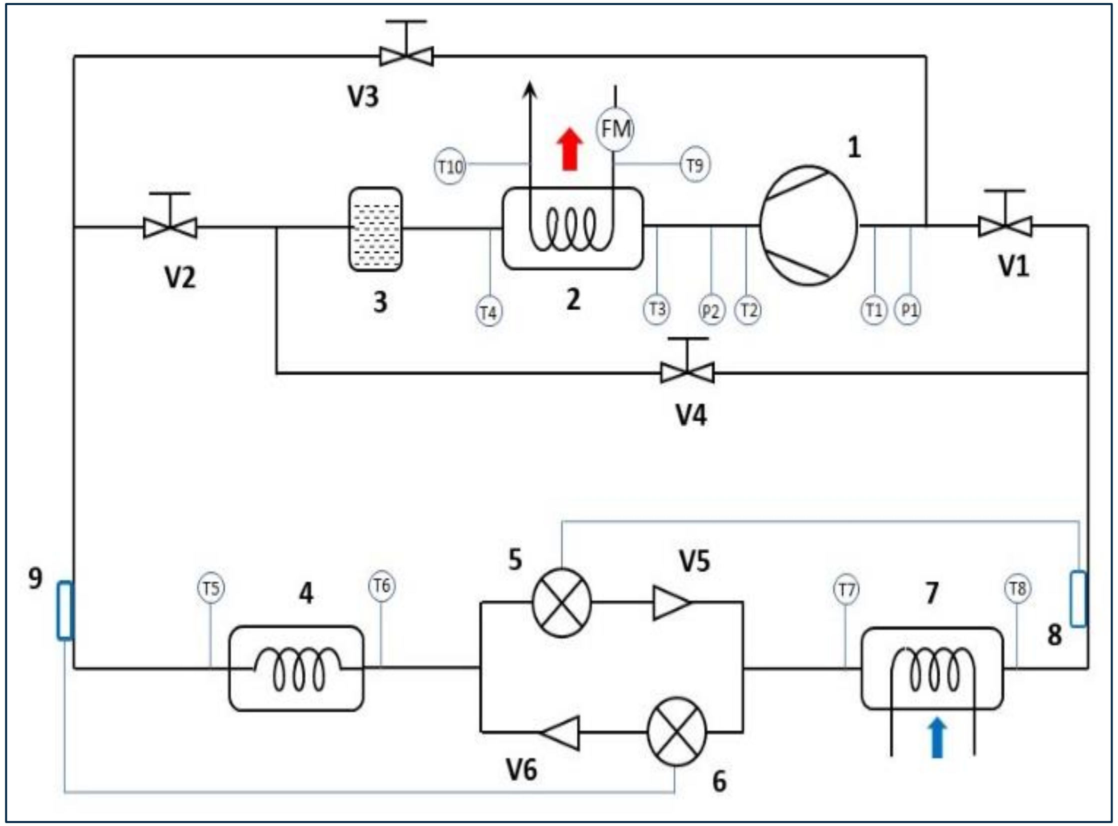
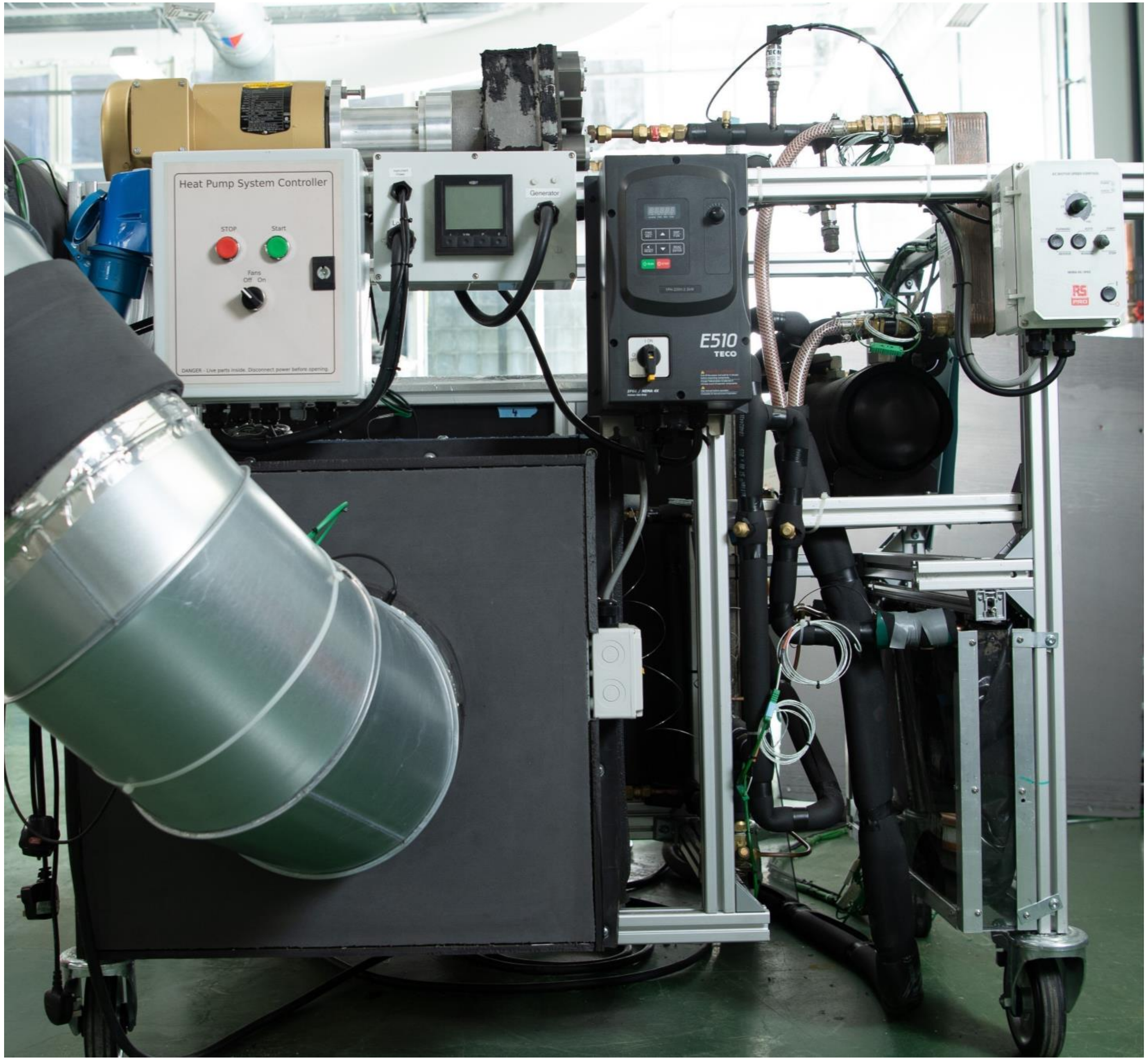
The prototype

- Off-the-shelf parts
- Water tank as heat storage
- Unoptimized
- Proved the concept





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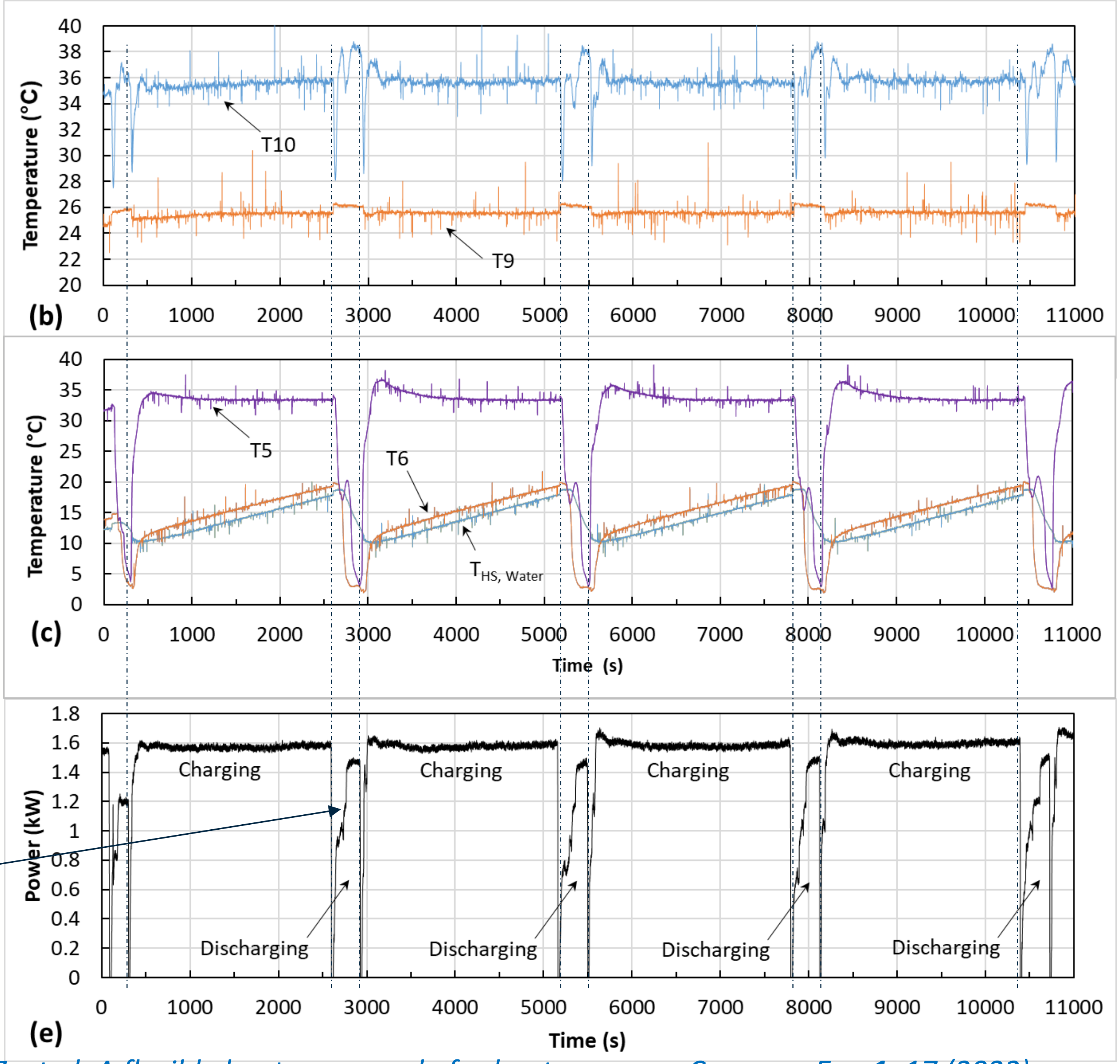
Experimental results

Keep the heat supply temperature and power constant

Water temperature change during charging and discharging

Power saving during discharging

Note: charging mode is the same as a single stage heat pump



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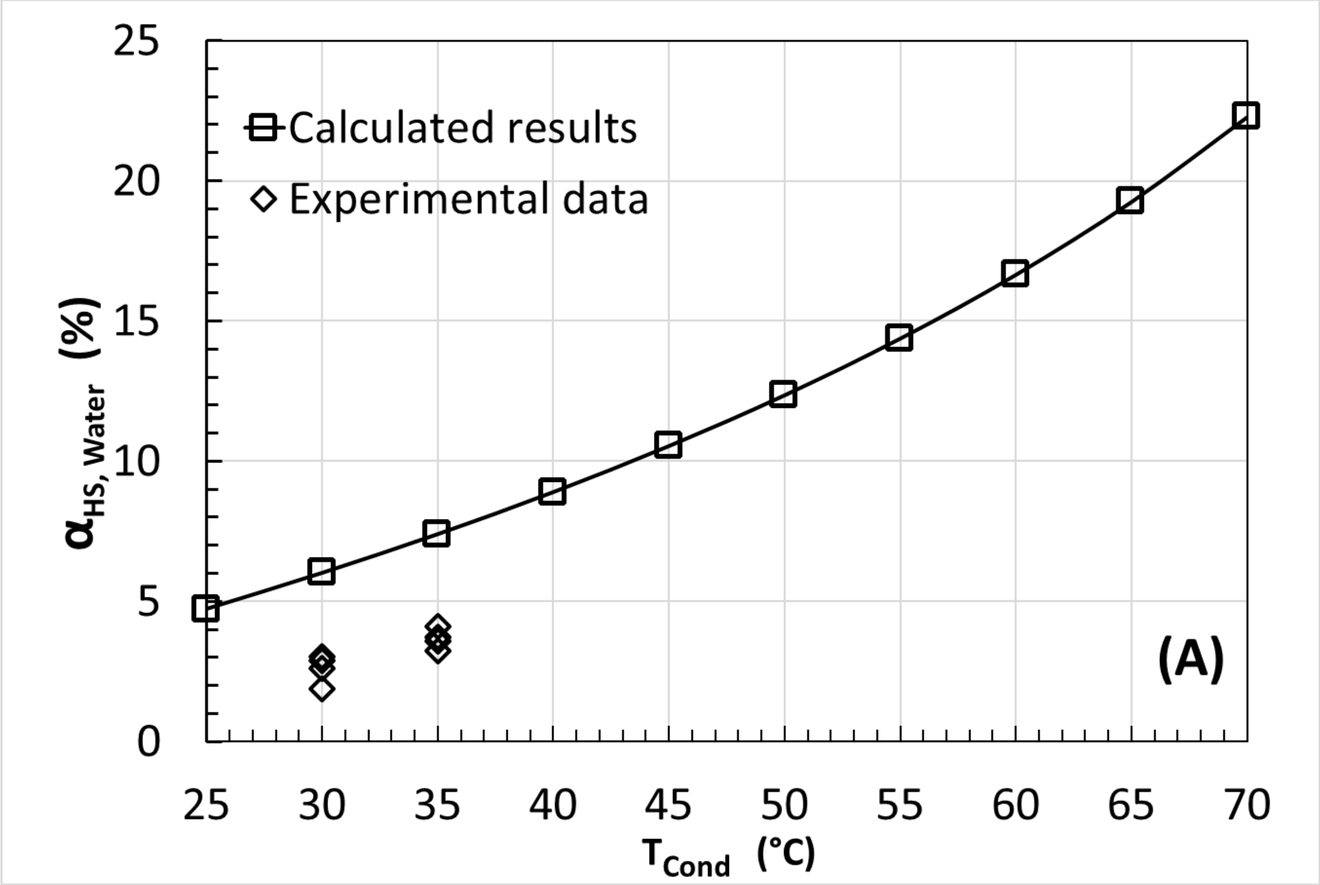
Prototype – experimental data vs. theoretical upper limit



$$\alpha_{Water\ tank} = \frac{\overline{COP}_{Flexible\ HP} - COP_{single\ stage}}{COP_{single\ stage}} \times 100\%$$

- Refrigerant: R134a
- Sensible heat storage (water)
- Heat source at around 0 ℃
- Supply temperature up to 35 ℃ (limited by our compressor)
- Achieved 3.7% COP improvement @ T_{supply}=35 ℃
- Benefits increases as supply temperature increases.
- Extrapolation: Up to 10% improvement @ T_{supply}=60-65 ℃

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Thermodynamic essence of the flexible heat pump cycle

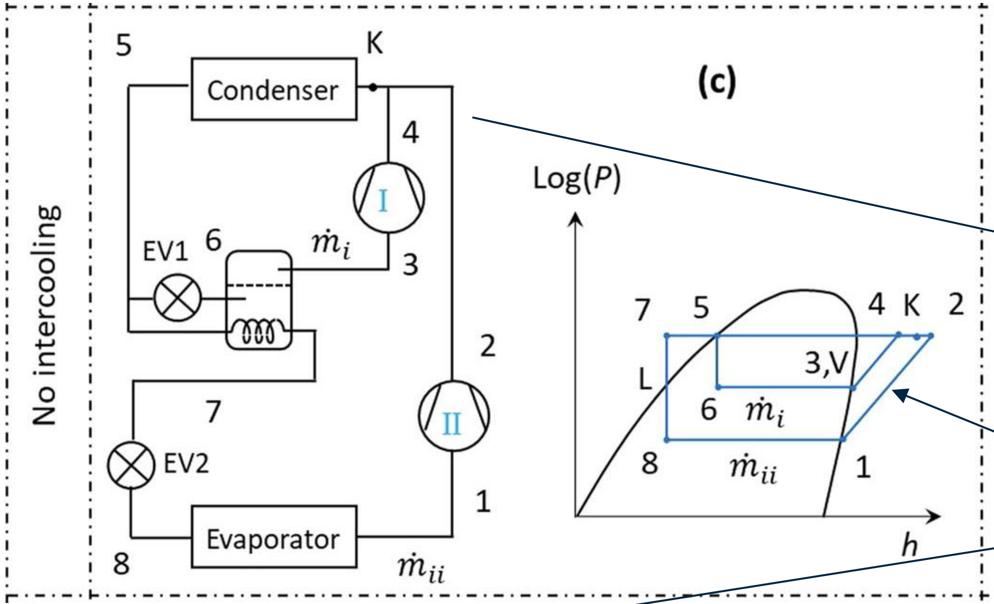
- Under ideal conditions, the flexible heat pump cycle is thermodynamically similar to two-stage heat pump cycles with full subcooling or flash gas removal, but no intercooling.

- the two-stage cycles recover and reuse some sensible heat carried by hot liquid refrigerant simultaneously using their high-stage compressor.

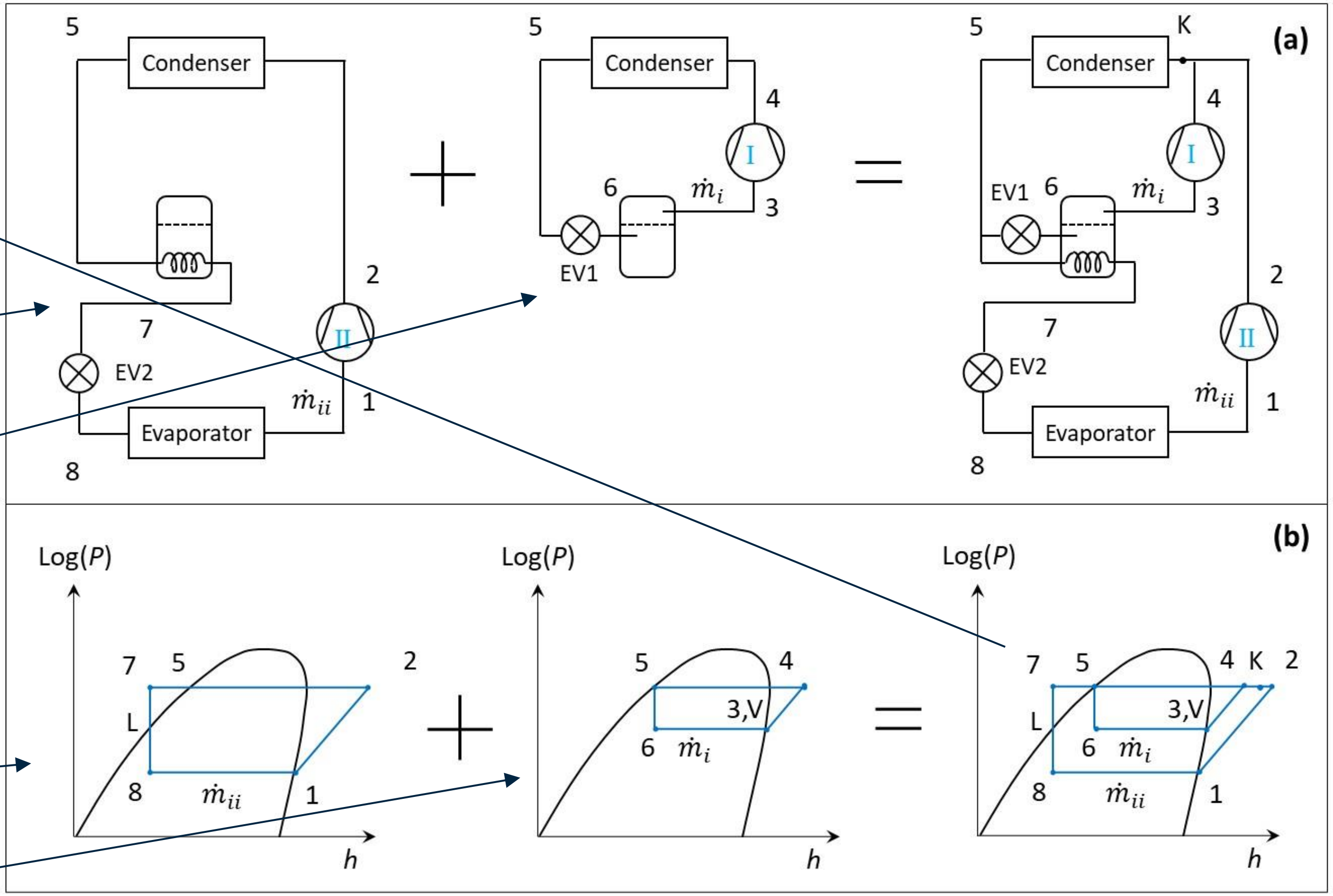
- the flexible heat pump cycle decouples the recovery and reuse of such heat in time using a heat storage.

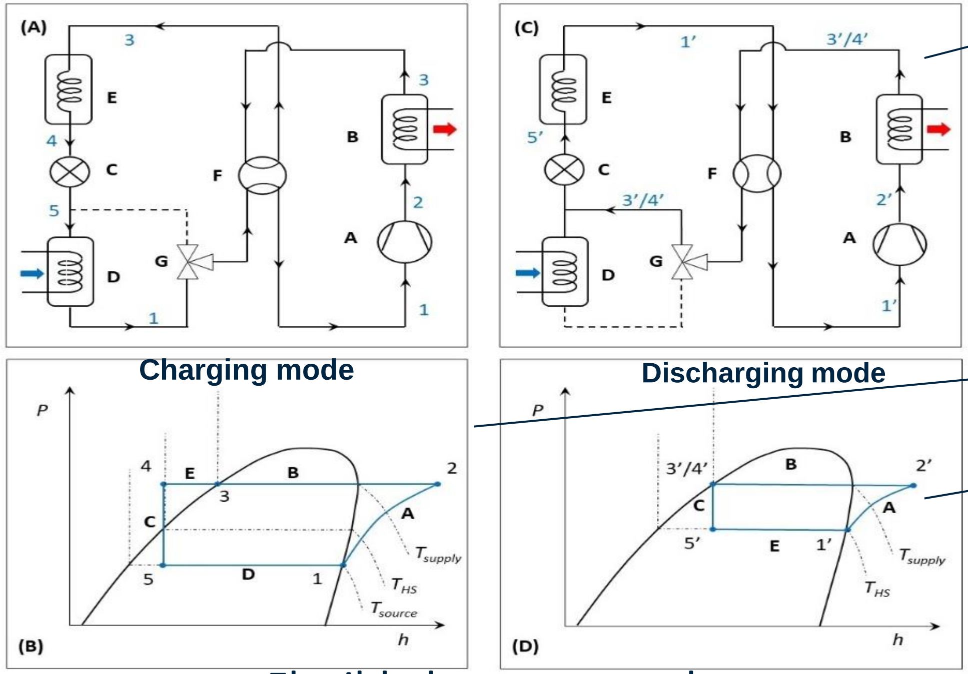
- Essentially, both the flexible cycle and these two-stage cycles can all partially avoid the recompression of flash gases generated during the throttling processes, and thus can save compression power.

Parallel compression sub-cooler (two-compressor)



Cycle superposition theory





Flexible heat ump cycle

Yu, Z., McKeown, A., Hajabdollahi Ouderji, Z. et al. A flexible heat pump cycle for heat recovery. Commun Eng ***1****, 17 (2022)*

Yu, Z., Ouderji, Z.H. A unified approach for the thermodynamic comparison of heat pump cycles. Commun Eng ***2****, 62 (2023)*

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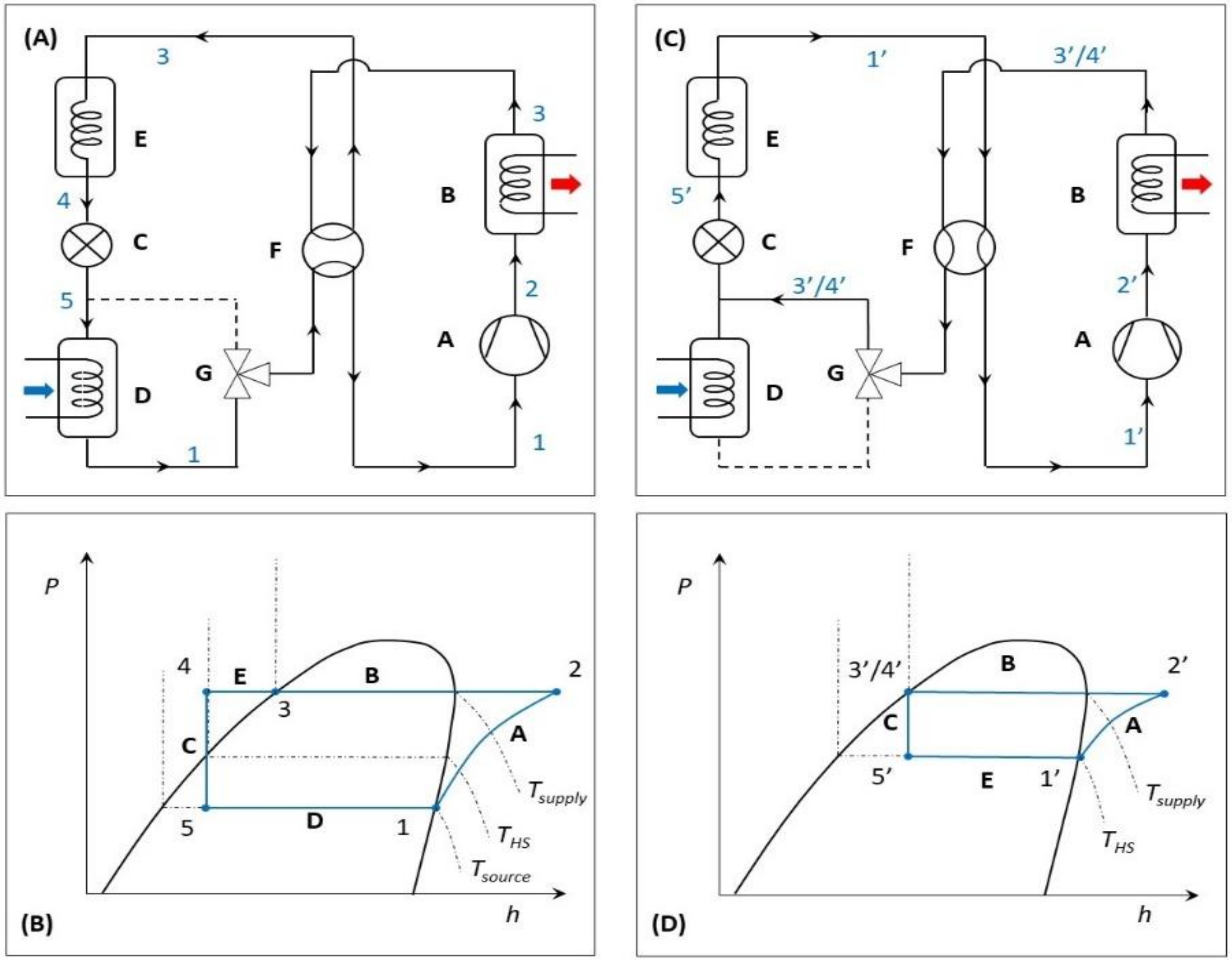
Application 1: Quasi-two-stage operation for compressor power reduction

- The recovery and storage of heat above heat source temperature allows the flexible heat pump to operate with a reduced power consumption.
- In theory, up to 20% more efficient than current conventional single stage heat pumps.

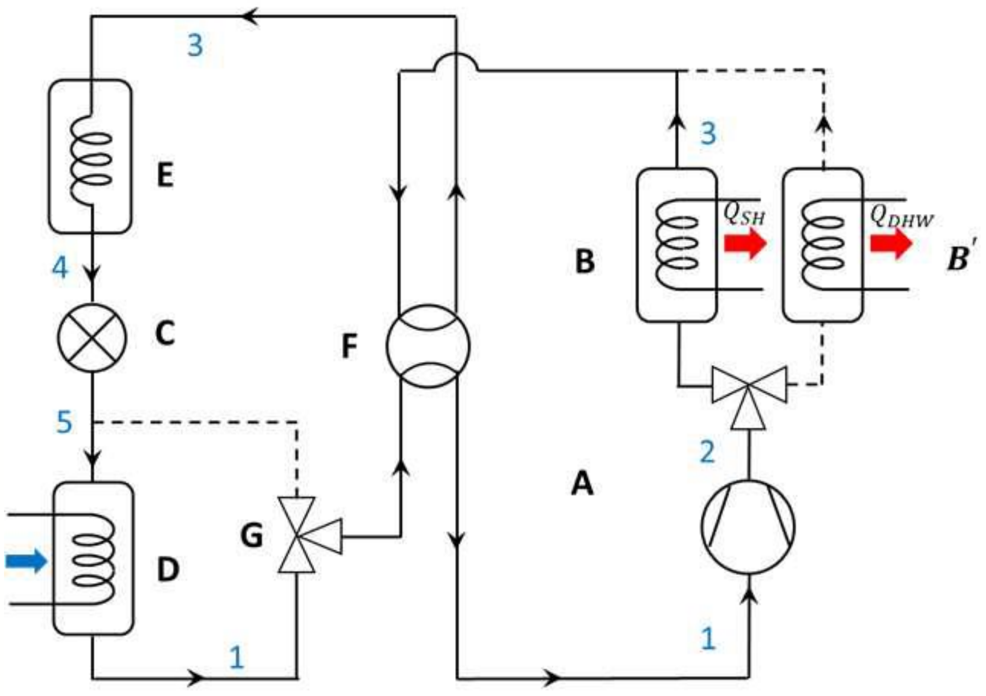


Charging mode **Discharging mode**

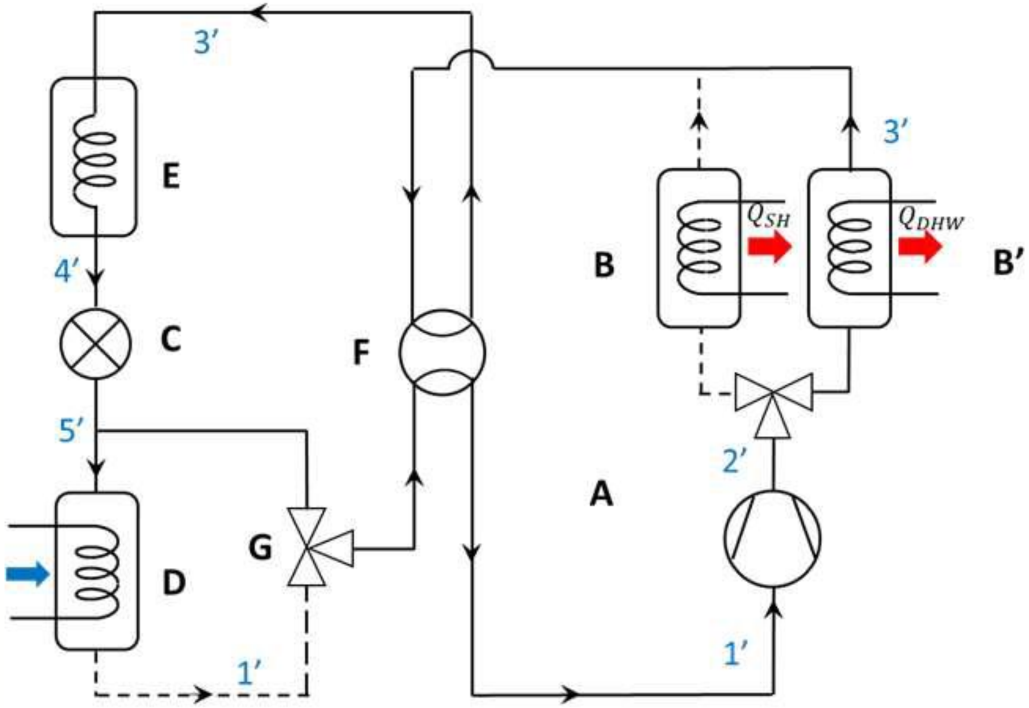
Yu, Z., McKeown, A., Hajabdollahi Ouderji, Z. et al. A flexible heat pump cycle for heat recovery. Commun Eng ***1****, 17 (2022)*

Application 2: Quasi-two-stage for supply temperature uplift

- The recovery and storage of heat above ambient/evaporation temperature allows the flexible heat pump to operate with high supply temperature.
- *Charging mode for space heating while heat is simultaneously stored in the TES*
- *Discharge mode for domestic hot water by using the heat that was previously stored in the TES.*



Charging mode for space heating

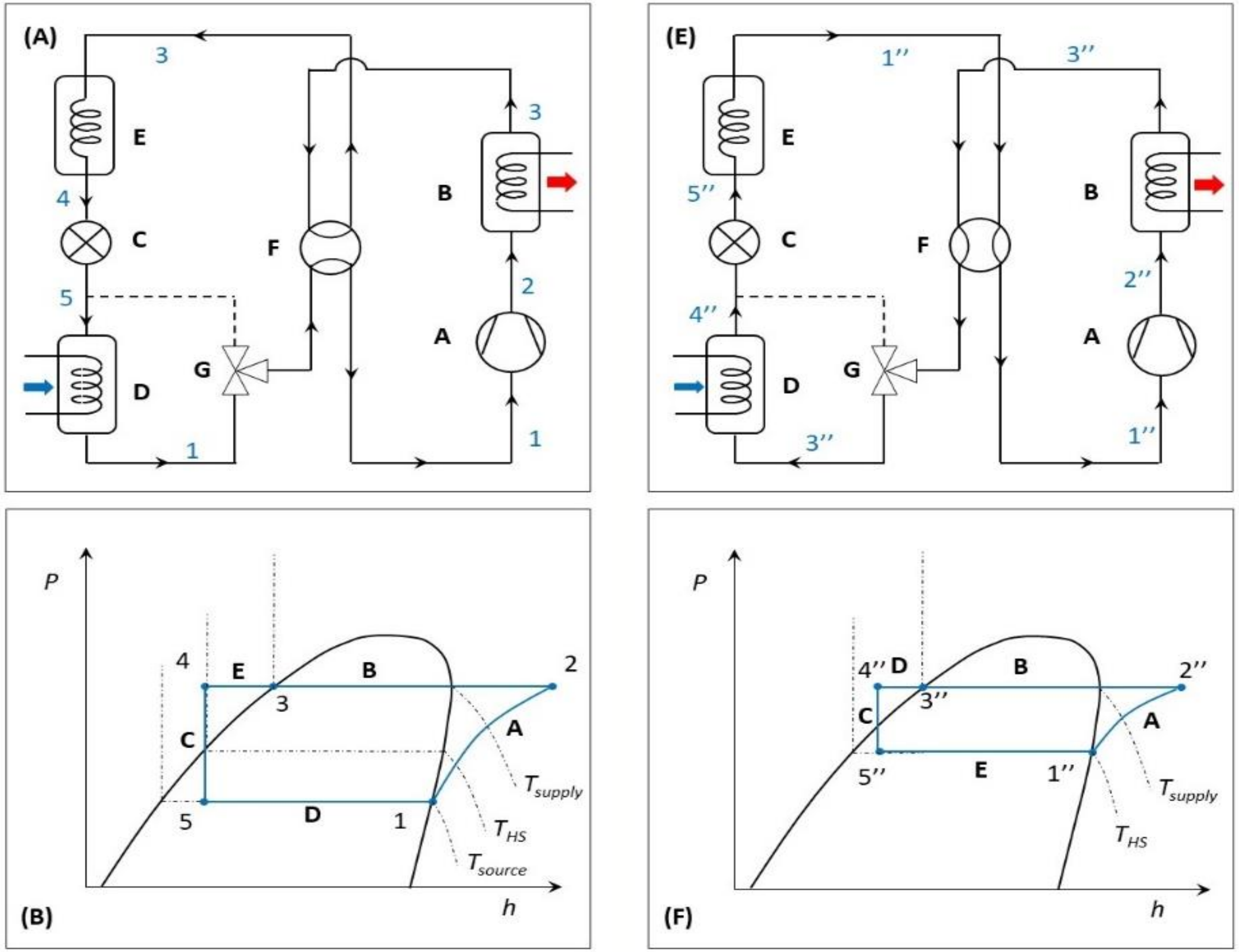


Discharging mode for domestic water

A flexible heat pump for combined domestic hot water and space heating supply Zahra Hajabdollahi, Andrew McKeown, Miryam Essadik, Narges Hassani Mokarram(a), Zhibin Yu, 26th International Congress of Refrigeration | August 21st-25th, 2023 | Paris, France

Application 3: Energy efficient defrosting for air source heat pump

- The recovered thermal energy from the cycle along with any recovered heat can be used to defrost the evaporator.
- Can save 5-17% energy depending on climate conditions.
- Uninterrupted heating supply during defrosting.
- Potentially eliminate the backup heater.



Charging mode

Discharging mode
with defrosting

*Yu, Z., McKeown, A., Hajabdollahi Ouderji, Z. et al. A flexible heat pump cycle for heat recovery. Commun Eng **1**, 17 (2022)*

Advantages of the Flexible Heat Pump Cycle

Cycle type	Number of compressors	COP	Defrosting
Single stage	1	Baseline	Reversed cycle /hot gas bypass; No heat supply
Two stage	2	Up to 20% more efficient in theory	Reversed cycle /hot gas bypass; No heat supply
Vapour injection	1 Vapour injection compressor	Up to 20% more efficient in theory	Reversed cycle /hot gas bypass; No heat supply
Flexible heat pump	1	Up to 20% more efficient in theory	Waste heat driven defrosting Continuous heat supply

Conclusions

- The flexible heat pump cycle introduces a heat storage device into the Evans-Perkins cycle to recover, store, and reuse part of the sensible heat carried by the hot liquid refrigerant from the condenser, achieving a higher coefficient of performance.

- Under ideal conditions, the flexible heat pump cycle is thermodynamically equivalent to two-stage heat pump cycles with full subcooling or flash gas removal, but no intercooling.

- From the energy recovery perspective, the two-stage cycles recover and reuse some sensible heat carried by hot liquid refrigerant simultaneously using their high-stage compressor, whereas the flexible heat pump cycle decouples the recovery and reuse of such heat in time using a heat storage.

- The refrigerant type has a strong impact on the effectiveness of all these performance-enhancing methods.

- The flexible heat pump cycle or two stage cycles can achieve a better COP improvement for wet or isentropic refrigerants which generate more flash gas during the throttling processes than dry refrigerants.

- Cycle superposition theory - A unified approach has been developed to model all these different heat pump cycle

Patent, publications, and press coverage:

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International Bureau
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(71) Applicant: THE UNIVERSITY COURT OF THE UNIVERSITY OF GLASGOW [GB/GB]; Gilbert Scott Building, University Avenue, Glasgow Strathclyde G12 8QQ (GB).
(72) Inventor: YU, Zhibin; 624, James Watt Building (South), University of Glasgow, Glasgow Strathclyde G12 8QQ (GB).
(74) Agent: MEWBURN ELLIS LLP; Aurora Building, Counterslip Bristol BS1 6BX (GB).
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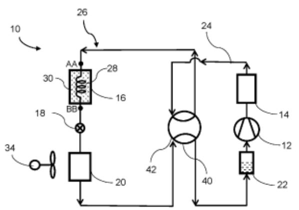
(54) Title: A HEAT PUMP SYSTEM



communications engineering

ARTICLE

https://doi.org/10.1038/s44172-022-00018-3 OPEN

A flexible heat pump cycle for heat recovery

Zhibin Yu[1,2], Andrew McKeown[1,2], Zahra Hajabdollahi Ouderji[1] & Miryam Essadik[1]

Heat pumps will play a key role in transitioning domestic heating to fossil-free sources. However, improvement in energy efficiency and cost reduction are still needed. Current vapour-compression heat pumps are built upon the Evans-Perkins cycle which was originally designed for refrigeration applications. Once hot liquid refrigerant has transferred energy to the central heating system, it leaves the condenser with sensible heat which can be utilized. Here we report a modified and flexible Evans-Perkins heat pump cycle integrating heat recovery and storage which is then used as an ancillary heat source for the heat pump's operation. It operates in a quasi-two-stage mode to theoretically save up to 20% in compressor power consumption compared with single-stage cycles. We build a prototype with off-the-shelf parts and demonstrate a practical 3.7% power saving at a heat production temperature of 35 °C. Power saving will further increase with heat supply temperature. We also qualitatively show that hot refrigerant exiting the condenser can be directly used for

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ARTICLE

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A unified approach for the thermodynamic comparison of heat pump cycles

Zhibin Yu[1] & Zahra Hajabdollahi Ouderji[1]

The flexible heat pump cycle introduces a heat storage device into the Evans-Perkins cycle to recover, store, and reuse part of the sensible heat carried by the hot liquid refrigerant from the condenser, achieving a higher coefficient of performance than the latter. In this paper, we develop a unified approach, namely cycle superposition to allow comparison of the flexible heat pump cycle with other performance-enhancing cycle layouts including two-stage cycles with intercooling, subcooling, flash gas removal, or their combinations. We show that under ideal conditions, the flexible heat pump cycle is thermodynamically similar to two-stage heat pump cycles with full subcooling or flash gas removal, but no intercooling. From the energy recovery perspective, the two-stage cycles recover and reuse some sensible heat carried by the hot liquid refrigerant simultaneously using their high-stage compressor, whereas the flexible heat pump cycle decouples the recovery and reuse of such heat in time using a heat storage. However, the irreversible heat transfer via real heat exchangers during charging and dis...

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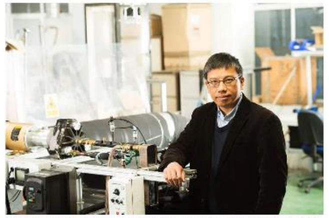
Another area attracting lots of innovation is energy storage. Many domestic solar installations already incorporate lithium batteries for when it's cloudy or dark. Larger scale storage is also becoming a reality, and heat-pump technology isn't standing still either. At Glasgow, Yu has developed a new, flexible pump that incorporates a heat-storage device between the condenser and the expansion valve.



Thermodynamic advantage Zhibin Yu with a prototype of the new flexible heat pump. (Courtesy: University of Glasgow)

This device takes some of the heat that would otherwise be lost and makes it available for the heat pump's operations. For example, the auxiliary heat could be used to defrost the heat pump's outdoor unit, as is regularly required when ambient temperatures fall below about 6 °C. Overall, Yu thinks a 10% improvement in efficiency is feasible with his design, which he believes would "make a big difference when you look at the payback period" for installing heat

cosy homes oxfordshire

New extra efficient heat pump unveiled by professor

In a new paper published in the journal *Communications Engineering*, researchers from the University of Glasgow outline how their flexible heat pump technology provides an elegant and low-cost solution.

The team led by Professor Zhibin Yu, have developed a new type of heat pump, a flexible heat pump technology, which could help households and businesses save on their energy bills and reduce carbon emissions.

The new designs help to solve the problems of current heat pumps by integrating heat storage – a small water tank and a coil of copper tube.

RETROFIT NEWS

THE FINANCIAL

THE WORLD'S BEST DIGITAL BANK FOR BUSINESS

Next- Gen Heat Pump Could Cut Energy Bills and Carbon Emmissions

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TECHNOLOGY

How heat pumps of the 1800s are becoming the technology of the future

Innovative thinking has done away with problems that long dogged the electric devices — and both scientists and environmentalists are excited about the possibilities

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It was an engineering problem that had bugged Zhibin Yu for years — but now he had the perfect chance to fix it. Stuck at home during the first UK lockdown of the Covid-19 pandemic, the thermal engineer suddenly had all the time he needed to refine the efficiency of heat pumps: electrical devices that, as their name implies, move heat from the outdoors into people's homes.

The pumps are much more efficient than gas heaters, but standard models that absorb heat from the air are prone to icing up, which greatly reduces their effectiveness.

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TODO SOBRE EFICIENCIA ENERGÉTICA

Investigadores ingleses buscan colaboradores para desarrollar una bomba de calor de última generación

Investigadores de la Universidad de Glasgow han desarrollado un nuevo tipo de bomba de calor, una tecnología de bomba de calor flexible, que podría ayudar a los hogares a ahorrar en sus facturas de energía y contribuir a alcanzar los objetivos de emisiones netas cero. Actualmente, están buscando colaboradores para impulsar el desarrollo de esta tecnología de bomba de calor flexible

future Net Zero

INSPIRE COMMIT EDUCATE

Glaswegian heat pump to accelerate the UK's race to low carbon heat

The so-called "flexible" technology integrates a heat source that could potentially reduce the pump's power consumption

Image: University of Glasgow

A new heat pump that can be 10% more efficient than existing models in the UK market has been developed by scientists from the University of Glasgow.

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Thanks for listening!

Happy to take questions!

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