A Review of Recent Residential Heat Pump Systems and Applications in Cold Climates

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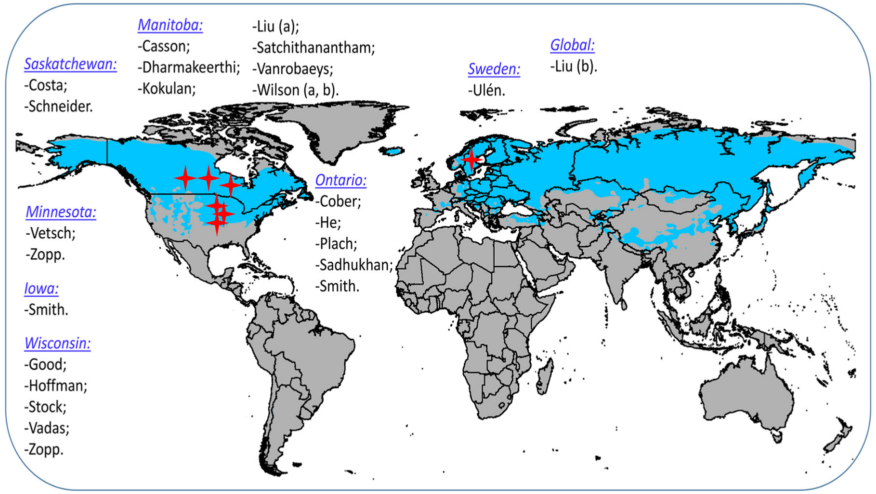
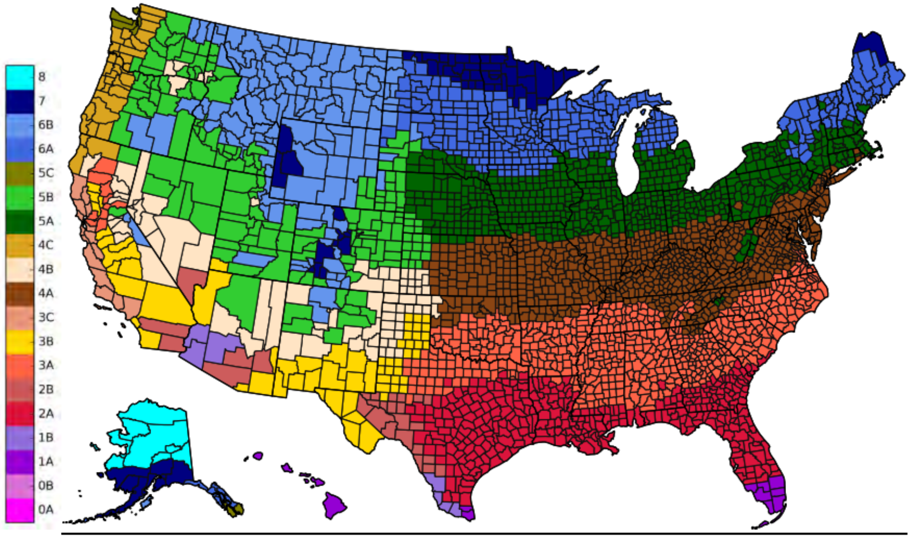
Backgrounds

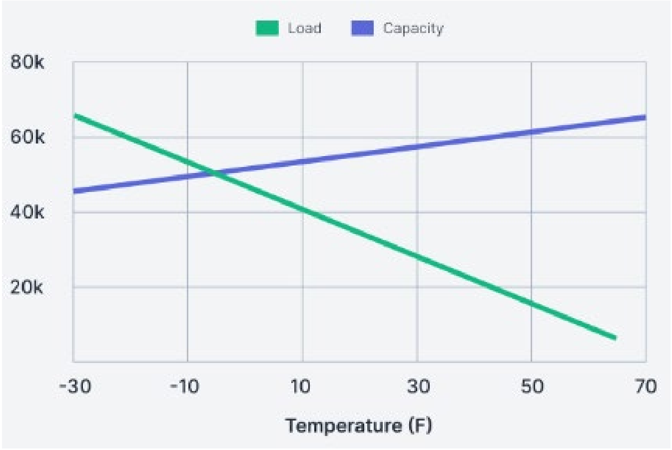
- Numerous regions worldwide experience polar climates.
- Cold weather causes a large degradation of heat pump performances.
- Heat pump is used for space heating and water heating.



Cold Climate Regions Around the World[1]



Climate Zones for United States Counties[2]



Heat Pump Capacity Change[3]

1. Liu, Jian, et al. "Agricultural water quality in cold climates: processes, drivers, management options, and research needs." *Journal of environmental quality* 48.4 (2019): 792-802.
2. ANSI/ASHRAE Addendum a to ANSI/ASHRAE Standard 169-2020
3. https://carbonswitch.com/best-cold-climate-heat-pump/

Cold Climate Heat Pumps

- A cold climate heat pump (CCHP) is specifically designed for cold climates and effectively extends its operating ambient temperature.
- The US DOE runs the residential CCHP Technology Challenge.
- The Challenge has two segments: one for a CCHP optimized for 5°F (-15°C) operation and the other for a CCHP optimized for -15°F (-26°C) operation.

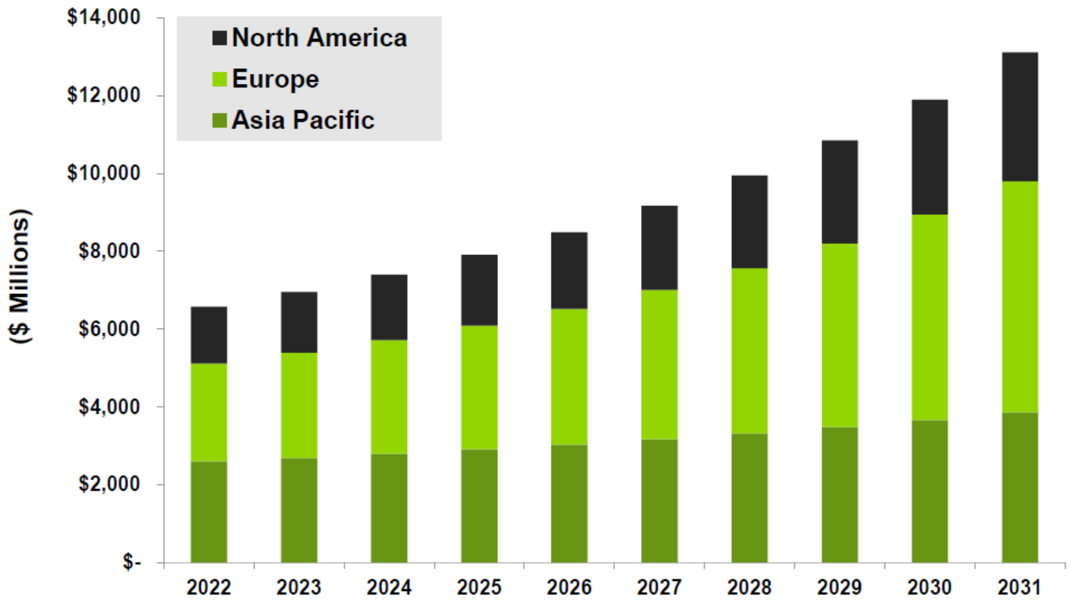
Product Prototype (Late 2021 / Early 2022)

Lab Testing (2022)

Field Testing (Winter 2022-2023 or 2023-2024)

Deployment Programs / Commercialization (2024)

CCHP Technology Challenge Timeline[1]



Residential Heat Pump Revenue by Region, Cold-Climate World Markets: 2022-2031[2]

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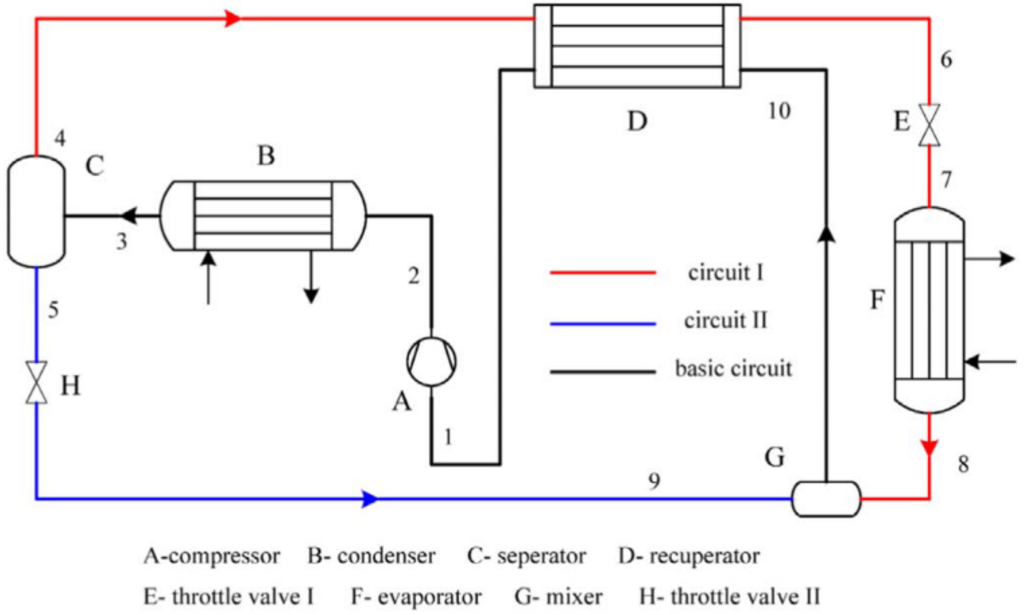
1. https://www.energy.gov/eere/buildings/residential-cold-climate-heat-pump-challenge
2. https://guidehouseinsights.com/reports/cold-climate-heat-pumps

Cold Climate Heat Pumps - Challenges

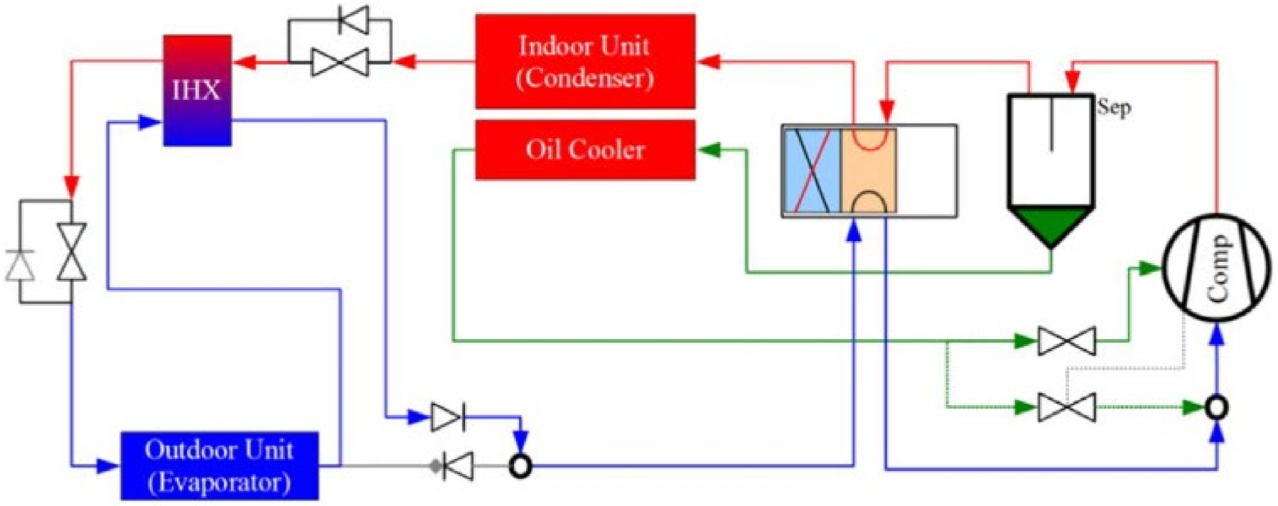
- High discharge temperature and pressure ratio at low ambient temperatures reduce the efficiency and heating capacity of ASHP systems.
- Frost on outdoor heat exchanger coil degrades thermal performance, reducing airflow, heat absorption, and overall performance (Up to capacity -43% and COP -30%).
- High discharge temperature can cause the lubricant to break down, forming a carbon residue.
- Low suction temperature can cause the refrigerant to enter the compressor in a two-phase form rather than vapor, resulting in compressor failure.

Air Source Heat Pumps - Advancement

- Different system configurations were designed to improve performance in cold climates.



An auto-cascade heat pump cycle[1]



An oil-injected system[2]

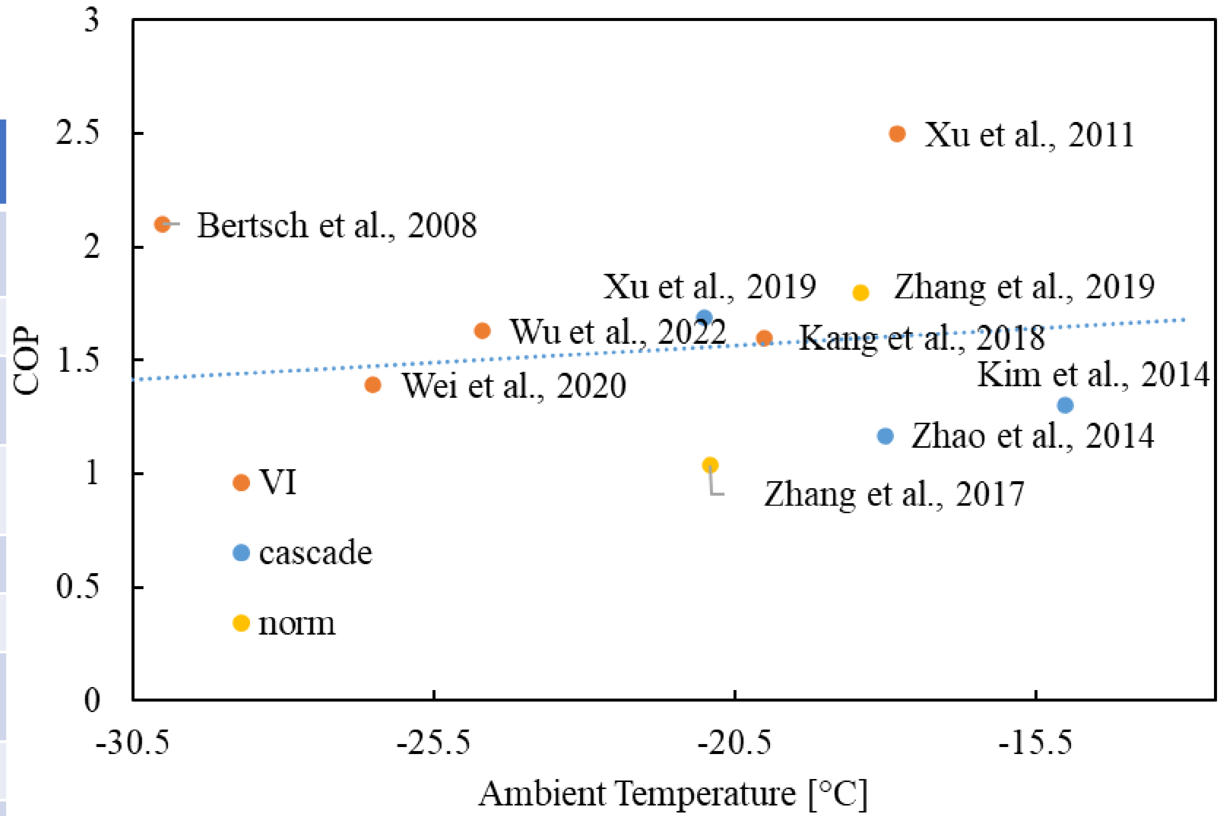
1. Zhao, Li, Nan Zheng, and Shuai Deng. "A thermodynamic analysis of an auto-cascade heat pump cycle for heating application in cold regions." Energy and buildings 82 (2014): 621-631.
2. Horton, W. Travis, Eckhard A. Groll, and James E. Braun. Development of a high-performance cold climate heat pump. No. DOE-Purdue-0003842. Purdue Univ., West Lafayette, IN (United States), 2014.

Air Source Heat Pumps - Performances

- Comparison of ASHP performance

ASHPs studies in recent 25 years

Authors, year	COP	Ambient Temp. [°C]	Cycle Type	Refrigerant	Discharge Temp. [°C]
Bertsch and Groll, 2008	2.1	-30.0	VI	R410A	93.0~102.0
Xu et al., 2011	2.5	-17.8	VI	R410A	-
Kim and Kim, 2014	1.3	-15.0	cascade	R410A/R134a	80.0~90.0
Zhang et al., 2017	1.1	-20.9	-	R22	-
Kang et al., 2018	1.6	-20.0	VI	R410A	97.3~101.2
Xu et al., 2019	1.7	-21.0	cascade	R404A/R134a	93.9~91.4
Zhang et al., 2019	1.8	-18.4	-	R410A	-
Wei et al., 2020	1.4	-26.5	VI	R410A	90.6
Wu et al., 2022	1.6	-24.7	VI	R410A	-



ASHPs COP vs. Ambient Temperature

Air Source Heat Pumps - Shortcomings

- Maximum COP of advanced systems under low ambient temperatures is still low concerning their primary energy ratio.
- Heating capacity needs improvement to meet building heating loads, especially in extreme conditions.
- Further research on system start-up at low temperatures and year-round control strategy is necessary for system reliability.

Cold Climate Heat Pumps with Other Sources

Residential ASHP[1]

Solar-Assisted Heat Pump[2]

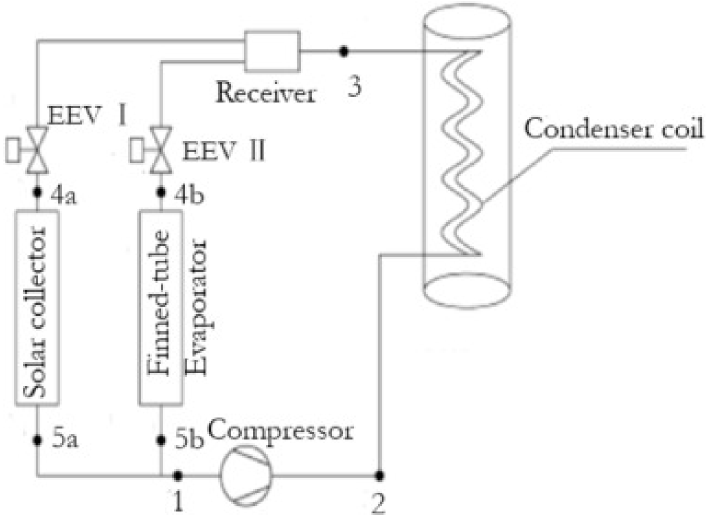
Ground Source Heat Pump[3]

Water Source Heat Pump[4]

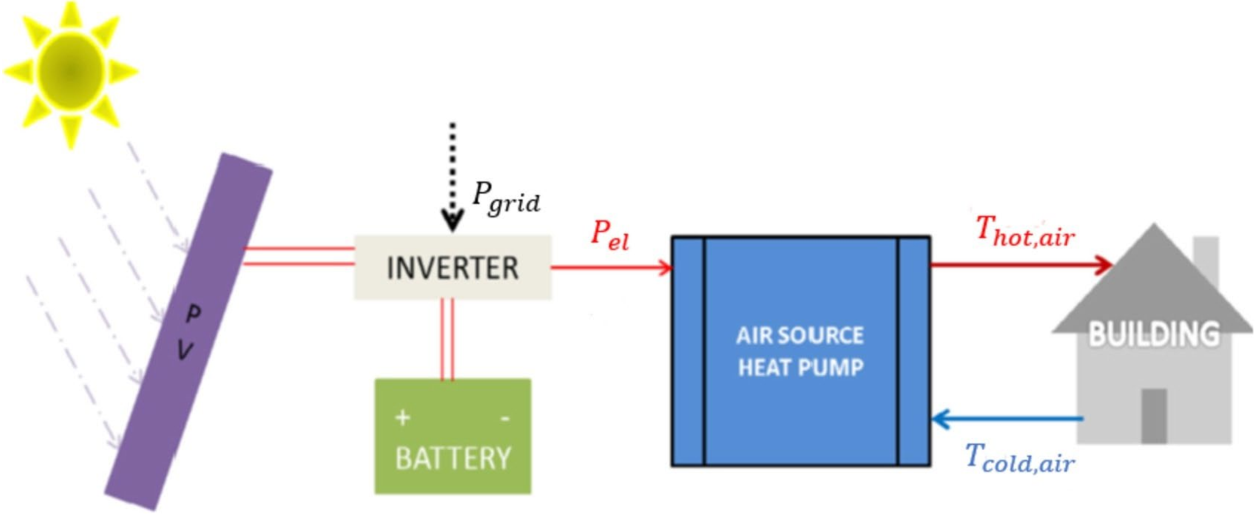
1. https://www.ukalternativeenergy.co.uk/projects/ashp-solar-pv-battery-storage-beeston/
2. https://www.uswitch.com/gas-electricity/green-energy/air-heat-pump/
3. https://www.carolinacountry.com/departments/energy-sense/geothermal-heat-pumps-2
4. https://www.hydroscot-energies.co.uk/renewables/heat-pumps/water-source-heat-pumps/

Solar Assisted Heat Pumps

- Solar assisted heat pumps typically consist of two types of systems: one that uses solar collectors and another that utilizes solar photovoltaic (PV) panels.



A combined solar/air dual-source heat pump water heater system[1]



Air source heat pump heating system coupled with PV modules[2]

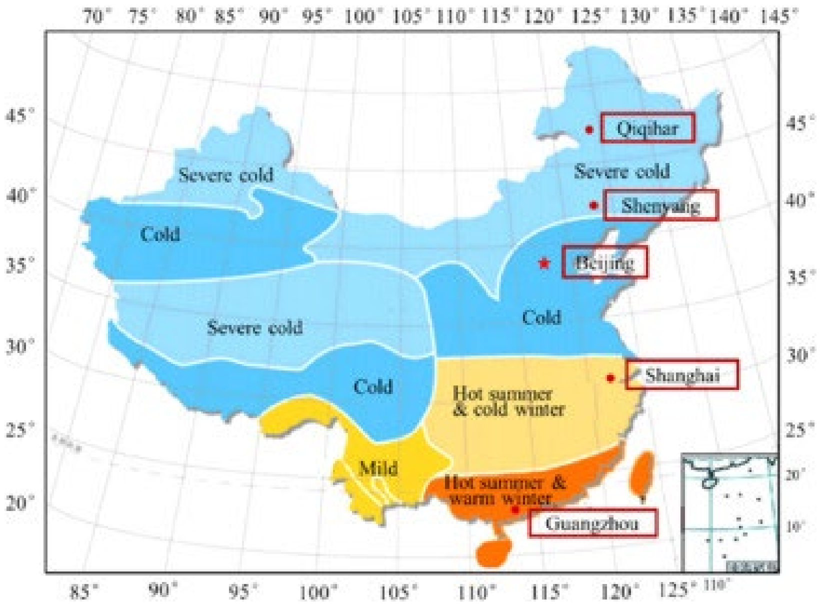
1. Deng, Weishi, and Jianlin Yu. "Simulation analysis on dynamic performance of a combined solar/air dual source heat pump water heater." Energy Conversion and Management 120 (2016): 378-387.
2. Bellos, Evangelos, et al. "Energetic and financial evaluation of solar assisted heat pump space heating systems." Energy conversion and management 120 (2016): 306-319.

Solar Assisted Heat Pumps - Shortcomings

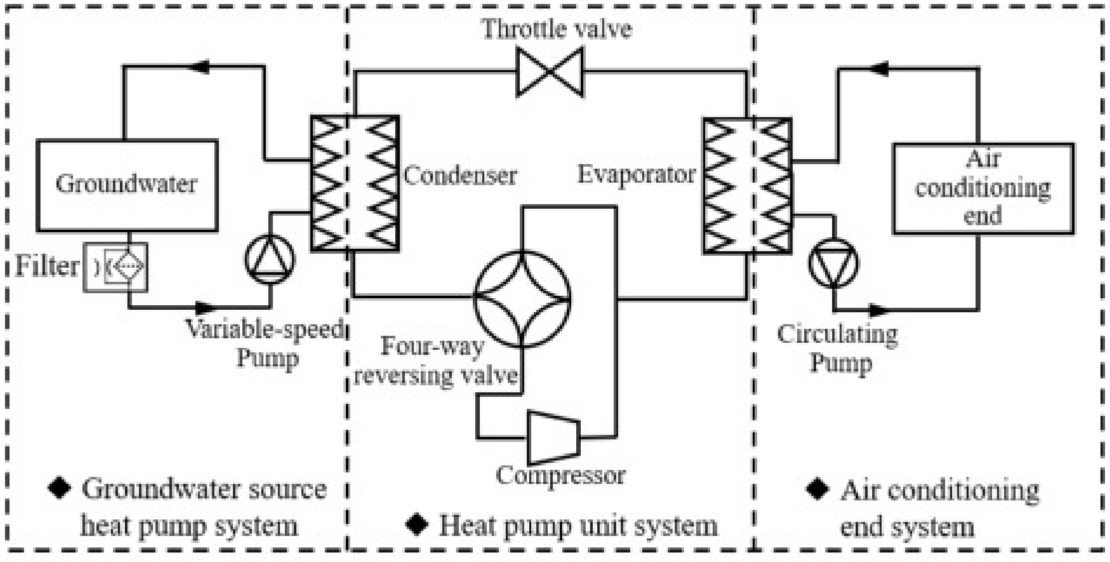
- Inconsistent methodologies, models, and boundary conditions limit the market promotion of solar-assisted ASHP systems.
- The gap between simulation/lab testing and real-world application requires standard testing conditions, a common simulation tool, and field-testing data.
- Limited studies on PV-ASHP require solving practical problems, optimizing system structure and operation, and component capacities.
- Lack of standardized performance indicators and consideration of environmental and economic parameters hinders system evaluation and comparison.
- Combining multiple systems can provide better energy solutions for buildings by overcoming individual system limitations.

Water Source Heat Pumps

- Water Source HP (WSHP) systems offer better economic benefits than ASHP systems.
- Annual costs of WSHP systems are 13.5% to 30.1% lower than ASHP systems in cities like Qiqihar, Shenyang, Beijing, Shanghai, and Guangzhou.



Climate zoning map of China

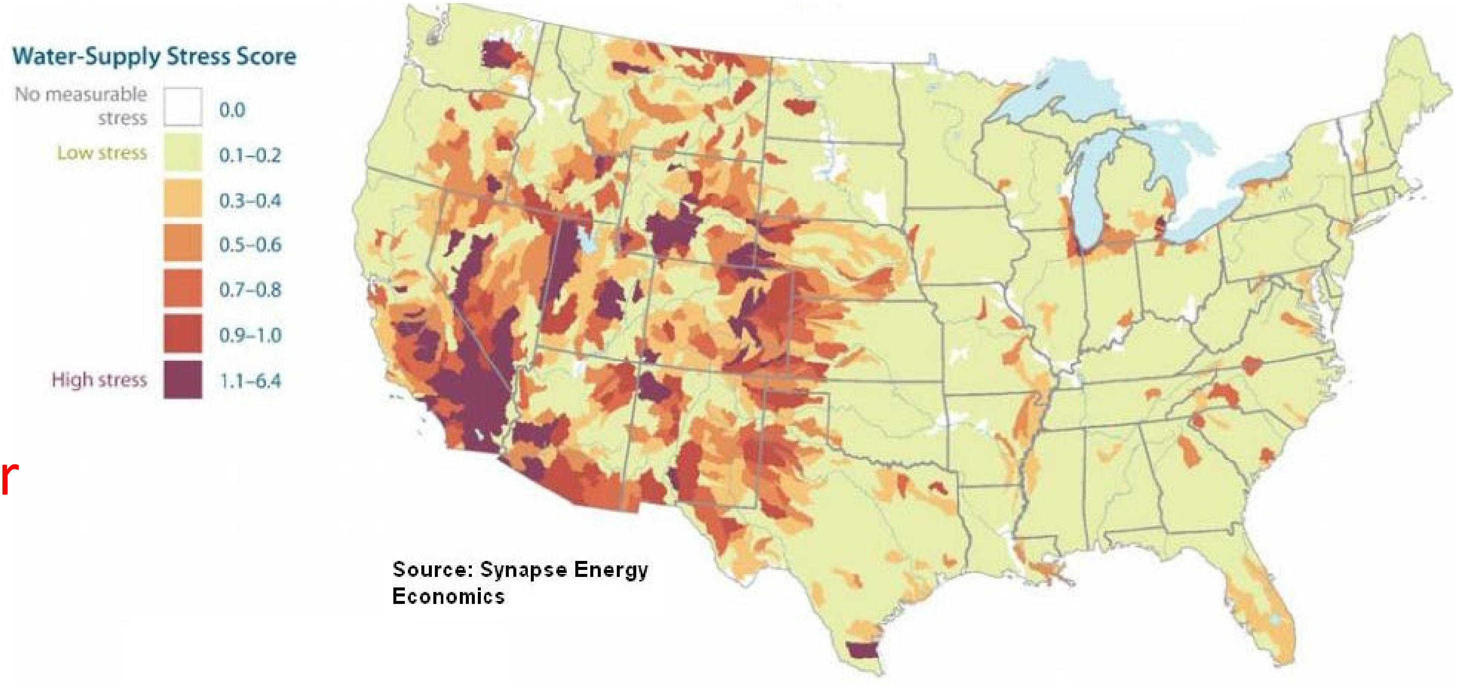


The operation principle of a groundwater source heat pump system

Liu, Zhijian, et al. "Suitability and feasibility study on the application of groundwater source heat pump (GWSHP) system in residential buildings for different climate zones in China." Energy Reports 6 (2020): 2587-2603.

Water Source Heat Pumps - Characteristics

- WSHPs offer stable performance with less temperature fluctuation in water sources.
- Minimal impact of COP’s seasonal variation on district heating systems.
- Efficient performance in cold climates.
- Limited applications due to large water bodies or storage tank requirements.
- Environmental regulations may hinder WSHP adoption.



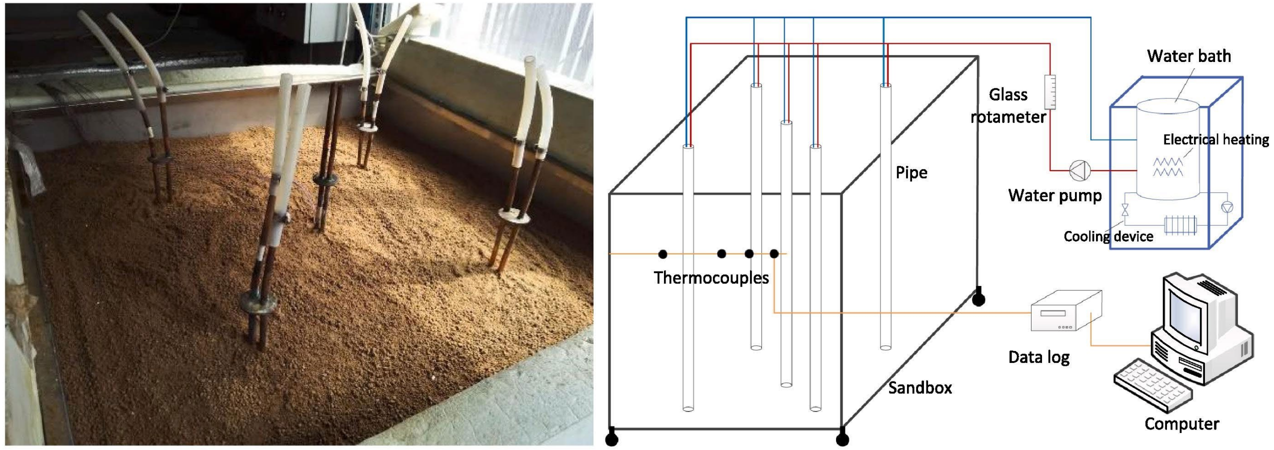
Source: Synapse Energy Economics

Water supply stress in the United States

https://www.windpowerengineering.com/report-thirsty-u-s-energy-production-collision-course-imperiled-water-supply/

Ground Source Heat Pumps

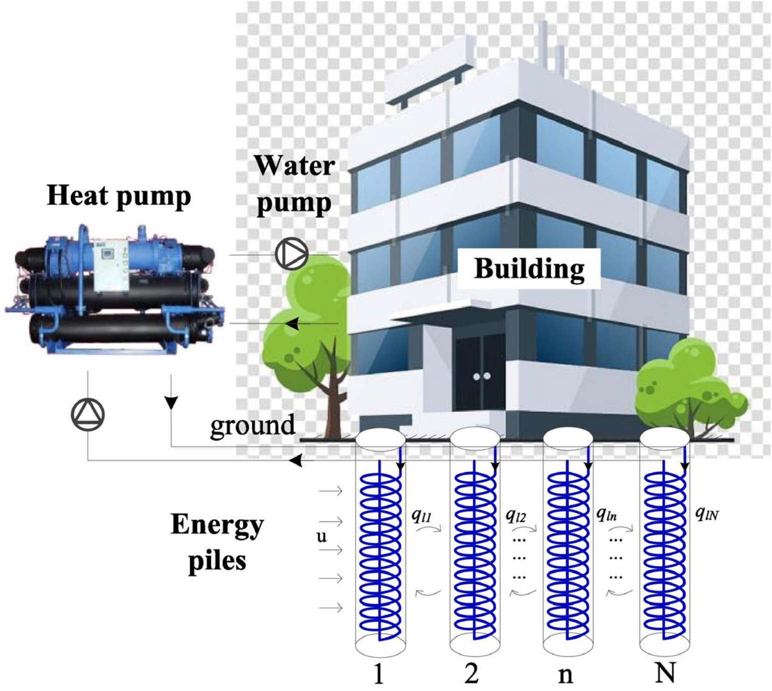
- A study evaluated the performance of a Ground Source Heat Pump (GSHP) system using spiral coil energy piles in Chinese cities.
- The system consumes only 51-62% of the power of a conventional boiler + AC system and is affected by soil thermal imbalance.



(a) Photos of experiment

(b) Schematic diagram

Sandbox experiment

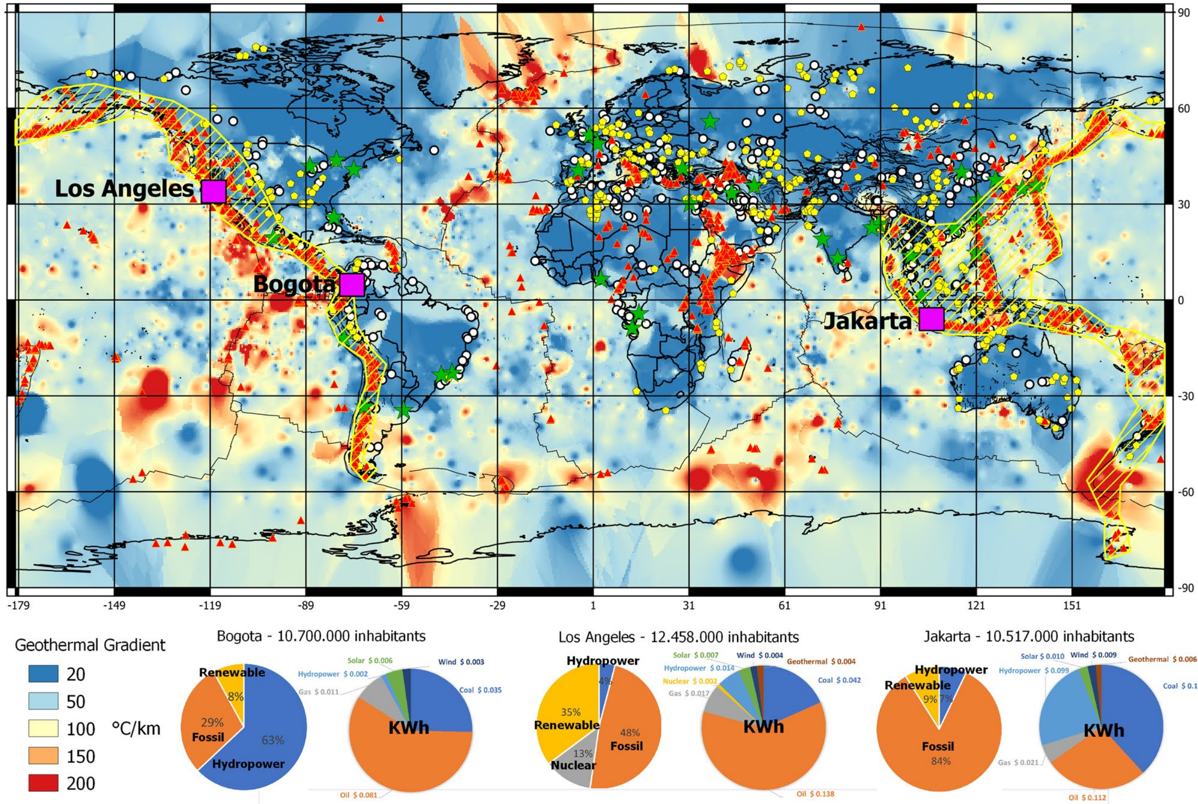


Schematic of GSHP using spiral coil energy piles with seepage

You, Tian, and Hongxing Yang. "Feasibility of ground source heat pump using spiral coil energy piles with seepage for hotels in cold regions." Energy Conversion and Management 205 (2020): 112466.

Ground Source Heat Pumps - Characteristics

- 40% more energy-efficient than ASHPs (location-dependent).
- Higher upfront costs, 10% lower expenses over 10 years vs. ASHPs.
- Direct expansion GSHPs excel in specific locations.
- Lower carbon emissions; need low-carbon power system integration.
- Benefits: efficiency, lower life cycle cost, environmental impact, reliability.
- Efficiency/savings depend on the HVAC system, gas/electricity prices.

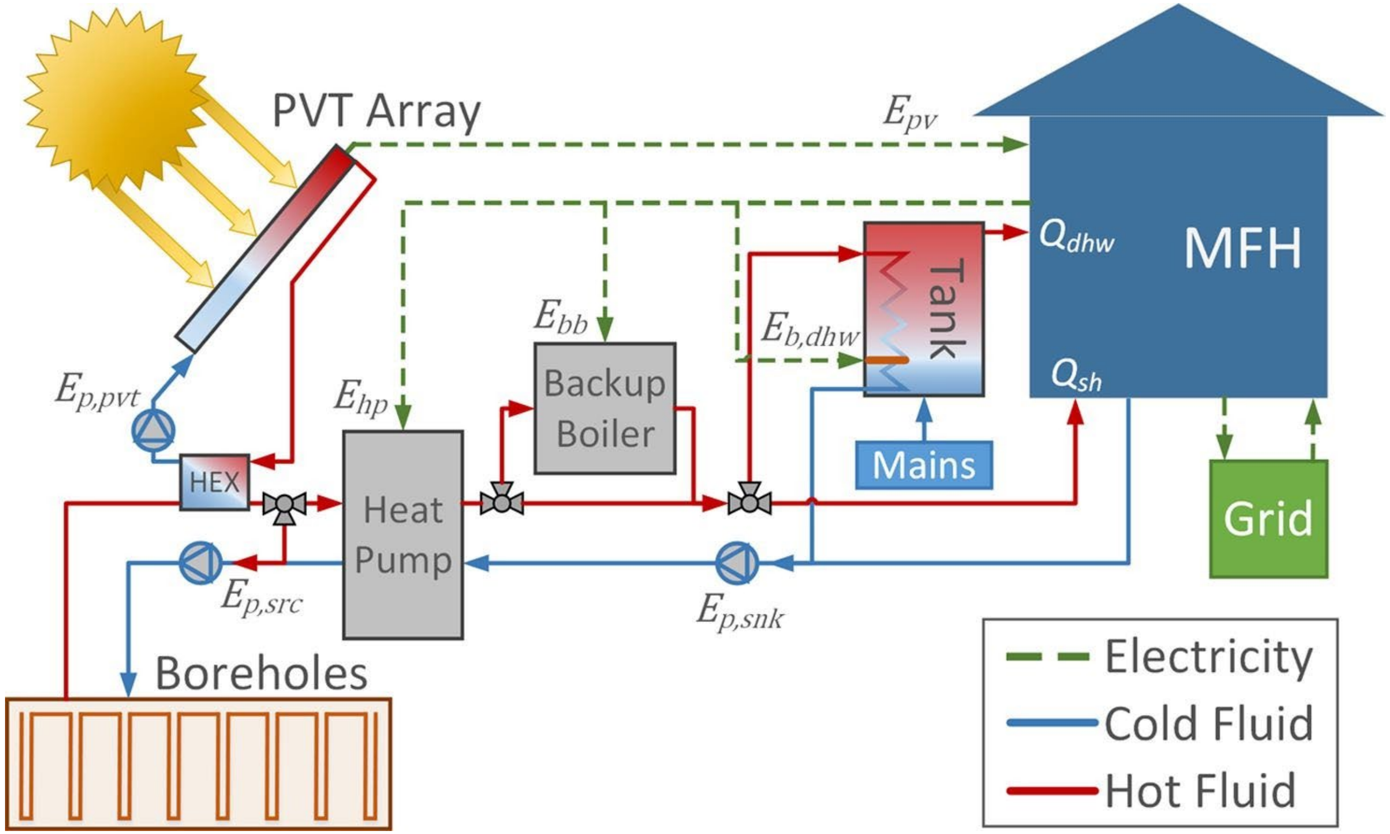


Worldwide distribution of geothermal gradient anomalies

Vargas, Carlos A., Luca Caracciolo, and Philip J. Ball. "Geothermal energy as a means to decarbonize the energy mix of megacities." Communications Earth & Environment 3.1 (2022): 66.

Renewable Integrated Heat Pump Systems

- Study evaluated PV+GSHP performance in multi-family houses in Sweden.
- PV reduces borehole length by 18% or spacing by 50%, while maintaining equivalent seasonal performance.
- PV+GSHP systems have higher costs but save up to 89% of land area.
- Reduction in land enabled by PV can increase GSHP penetration in MFH and promote solar energy diffusion in high-latitude markets.



PV/Thermal plus Ground Source Heat Pump systems[1]

1. Sommerfeldt, Nelson, and Hatef Madani. "In-depth techno-economic analysis of PV/Thermal plus ground source heat pump systems for multi-family houses in a heating dominated climate." Solar Energy 190 (2019): 44-62.

Current Challenges

1. Lack of clear decarbonization pathways, technology acceptance, and funding.
2. Public acceptance and awareness issues related to reliability, misperceptions, and misinformation.
3. Existing market structures and public perception hinder the penetration of cold climate heat pumps.
4. Lack of standards and mandatory policies constrain the deployment of specific heat pumps systems like GSHP and WSHP.
5. Limitations of the electrical network and potential need for additional grid infrastructure investments.
6. Proper sizing and installation are required to achieve design objectives and overcome adoption barriers.

Conclusions

1. Heat pump systems are an ecologically sustainable way to lower the carbon footprint of buildings due to their efficiency and minimal added initial cost.
2. Two-stage compression and VI systems show potential for performance and cost in ASHP systems, but discharge temperature and COPs need improvement.
3. Defrost penalty significantly reduces energy efficiency and heating capacity, making it a crucial factor for CCHP application.
4. Low-temperature start-up technology and year-round control strategies are important but understudied.
5. SAHP and GSHP systems are better options in colder regions, but the choice depends on location, application, and environmental constraints.
6. Current barriers to CCHP systems include policy limitations, public acceptance, economic factors, lack of standards and funding, and insufficient studies on the electrical network.

Future Works

1. Develop multi-source heat pumps utilizing both solar energy and ground source energy, with efficient control coordination.
2. Use waste heat or low-grade heat for defrosting in cold climate regions and identify alternative heat sources.
3. Study advanced heat storage technology and heat exchanger design strategies.
4. Optimize configuration and refrigerant usage to address low discharge temperature in cold climate heat pumps.

- **Thank you!**
  - **Question?**

Acknowledgment

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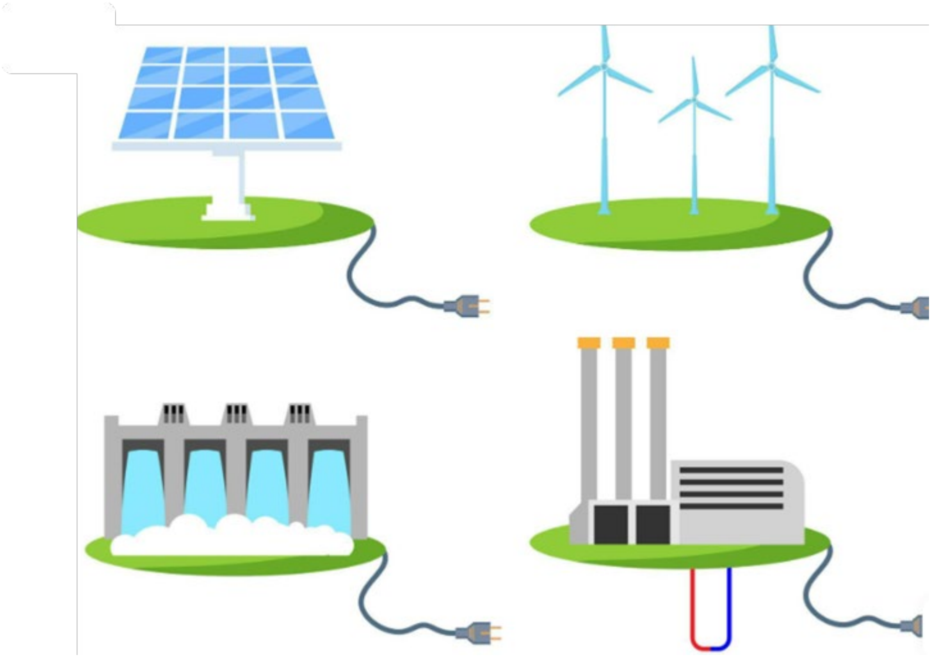
Systems with Additional Energy Sources

- Integrating systems with supplementary energy sources is an initial and intuitive solution.



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1. https://ecomerge.blogspot.com/2016/06/energy-to-power-tommorow.html