HVACC 4.0: Heating and cooling for the day after tomorrow

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Abstract. For achieving the 2°C goal of the Paris climate protocol, decarbonization of the building sector, which accounts for about 50% of the primary energy consumption [7], is planned for 2050. With a current annual building refurbishment rate between 0.4 and 1.2% in the EU it will be impossible to reach this objective. For getting on track, efficient and particularly affordable solutions fulfilling future-proof requirements are needed. This paper introduces the concept of HVACC 4.0, which stands for Heating, Ventilation, Air Conditioning and Chilling. The system architecture differs from state of the art HVACR, where the R stands for Refrigeration, in at least three points: (1) The innovative thermal storage and collector concept allows to harvest and store “low temperature heat and cold” on a daily basis, (2) in heating applications, the disruptive refrigerant cycle allows to more than double the Coefficient of Performance (COP) compared to air-water heat pumps and (3) in cooling applications, the nighttime harvesting of cold via unglazed PVT-collectors allows to boost the Energy Efficiency Ratio (EER) by a factor of >10 compared to split devices or cold water aggregates. HVACC 4.0 aims to provide a solution in form of an easy-to-install refurbishment kit. The design criteria for addressing the “4.0” in HVACC 4.0 have been (1) to exemplify the principle of “efficiency 1st”, (2) to maximize the share of Renewable Energies (RE) on total energy consumption, (3) to allow serving next generation low temperature District Grids (DG) and (4) to allow “more sector coupling”. As new and innovative RE sources with high collector yield, unglazed PVT-collectors (Photo Voltaic & Thermal) and thermally activated Sheet Pile Systems are discussed.

1. Introduction

For the EU, the following energy consumption related numbers are reported [1]:
1. Europe consumes half of its primary energy for heating and cooling
2. Most of thermal energy is consumed in buildings (space heating) and in industry (process heat)
3. Space cooling plays still a minor role, but will grow fast, mainly in developing countries [2]
4. About two thirds of thermal energy have fossil origin, only 13% are RE
5. DGs account for 9%, which is mainly waste heat from Combined Heat & Power (CHP)
6. For managing the energy transition, the electricity demand will rise dramatically due to increasing numbers of heat pumps and electric cars, making sector coupling more important

For realization of a “heat transition” in the building and industry sector, a bundle of measures is necessary:
1. Lower the energy consumption of buildings by insulation, which is out of tune with cost [3]
2. Replace oil and gas heaters by heat pumps, which is out of tune with 24h-availability of RE electricity
3. Increase the RE share for powering DGs, which is out of tune with the ban of coal and consequently also Combined Heat and Power (CHP) for sourcing 4G and 5G DGs
4. Maximize COP and EER, which is out of tune with rising market share of air-based heat pumps
5. Exploit new RE sources for sourcing heat pumps at higher source temperature than outside air
6. Exploit new RE sources for direct sourcing of cooling circuits instead of operating a condenser at high outside temperature like in case of split devices

In this paper the bullet points (2) to (6) are addressed. Regarding acronyms, please refer to the table at the end of the paper.
2. State of the art technologies

Figure 1 shows the COP of a brine-water heat pump as function of the sink temperature $T_{\text{sink}}$ for different values of the source temperature $T_s$ (left) along with a hydraulic example for combining a heat pump with ST-collectors and a storage (right) as investigated in SHC task 44 [4]. The well-known “adjusting screws” for increasing the COP are:

- Use of heat pumps with high heat pump efficiency $\eta_{\text{HP}}$ (e.g. water-water instead of air-water)
- Lower $T_{\text{sink}}$ as much as possible by use of area heaters (e.g. floor, wall or ceiling) instead of radiators
- Maximize $T_s$ by using RE sources with higher source temperature compared to air (air-water heat pump: $T_{\text{air}}$ down to -15°C) or brine (brine-water heat pump: $T_{\text{brine}}$=3…7°C)
- Optimize the refrigeration cycle for simultaneous heating and cooling such as realized e.g. with Variable Refrigerant Flow, also known as VRF-technology [5]

![Figure 1](image1.png)

Figure 1. COP of a heat pump as function of $T_{s}$ and $T_{\text{sink}}$ [6] (left) and hydraulic example (right) for combination of heat pumps with collectors and storages [4]

3. New technologies and expected results

3.1 Renewable energy sources

Figure 2 shows the worldwide energy consumption and RE shares for the sectors “Heating & Cooling”, “Transport” and “Power”. Important messages are: (1) With 26%, only the power sector has an appreciable RE share, (2) in the building sector accounting for 51% of total primary consumption, the RE share is with 10% low and (3) in the transport sector the RE share is with 3% very low, but will increase if electrification takes place. If we look at the total final energy consumption (slide 21 in [7]), the share of “modern RE” is 10.6%, where 2% are RE electricity, 3.6% Hydropower and 4.2% RE heat. Thereof about 0.2% are Solar Thermal (ST) and 0.3% Geo-Thermal (GT). Having in mind that the sun delivers each day 2.850 times the energy needed for “operation of our planet”, the RE share of ST and GT needs to be increased dramatically. Two examples for improving this situation are given.

![Figure 2](image2.png)

Figure 2. Energy consumption and RE shares (worldwide) by sectors [7]
A: PVT-collectors

PVT-collectors are hybrid collectors for co-generation of electricity and thermal energy. This design (market share < 0.5%) may be more attractive than classical “side by side installations” of PV- and ST-collectors, if the system architecture is optimized for taking full advantage of the collector capabilities to tri-generate electricity, heat and cold as needed in HVACR applications. This problem is illustrated in Figure 3:

![Figure 3](image)

**Figure 3.** IEA Task 60 approach for optimization of the system architecture for PVT-collectors: “The key issue is how to design optimized and reliable PVT-systems,” explained Jean-Christoph Hadorn, member of the IEA SHC Executive Committee (ExCo) and manager of Swiss firm Base Consultants” [8]

B: Thermally activated Sheet Pile System:

Even though the major part of radiation from the sun is absorbed by and stored in the ground, the share of near-surface geothermal is with 7.9% rather low [1]. To improve this situation, new types of geothermal collectors, such as thermally activated Sheet Pile Systems as shown in Figure 4 (left side), are beneficial. In winter, cold water emerging from the evaporator of a brine-water heat pump (right side) is fed through the thermal absorber. Due to the 6-month phase shift of T-profiles in 10…15m depth, the return temperature is by 2 to 4°C higher compared to brine-water heat pumps sourced from a borehole and even higher in case of an earth collector field.

The advantages are striking, especially if used in combination with shoreline stabilization such as occurring at dikes, sewers or the sea. In such applications, according to findings in a related research project at RWTH Aachen [9], the heat extraction power is with up to 400 W/m² much ahead of collector fields (10…35 W/m²) and boreholes (<20…70 W/m), which are today best practice geothermal heat sources for operation of brine-water heat pumps. If a Sheet Pile System is installed in flowing water such as a river, it is expected that the heat extraction power will be >1000W/m².

![Figure 4](image)

**Figure 4.** Concept of the Sheet Pile System as investigated in [9] (left) and connection to buildings via heat pumps (right) for generation of Domestic Hot Water (DHW) and Heat & Cold (H&C) for operation of area heaters like e.g. Floor Heaters (FH)
3.2 Concept description HVACC 4.0

Figure 5 shows a simplified sketch of the system architecture of HVACC 4.0 (left) and the disruptive refrigerant cycle (right) as an example for new building services. The following differences compared to best available technology (Figure 1) should be highlighted:

- **Multi Buffer Storage concept (BS1, BS2, BS3) instead of a single storage**
- **One storage (BS2) designed as a daily storage for “thermally useless medium” (10…30°C in summer, 15…40°C in winter), which acts as a virtual electric storage and enables sector coupling**
- **Cooling the daily storage in summer at night regeneratively via unglazed PVT-collectors at EER up to 60 [10] instead of using split or multi-split devices at EER \( \approx 2.5 \)**
- **Operation of the heat pump in winter at \( T_U > 10°C \) instead of at \( T_U < 7°C \) (borehole, collector field)**
- **Operation of cooling circuits at \( T = 18…20°C \) with medium from BS2 instead of using medium of 7…8°C from a cold water aggregates**
- **Maximize the primary electric and thermal collector yield by using unglazed PVT-collectors supplied in winter with very cold medium from BS3 [11] instead of using flat plate or vacuum tube collectors supplied with medium at temperatures close to the backflow from the heating circuits**
- **Tune the temperatures in the storage cascade to the needs of the building via two “Temperature Modification Devices” (TMD1/2) instead of using one heat pump and one storage (Figure 1)**
- **Direct condensation and evaporation via heat exchangers (HEX) located preferably inside the storages instead of using compact and less efficient plate HEX with large \( \Delta T_{HEX} \) (Figure 1)**
- **PVT-collectors w/o insulation on the back side (lower cost) for additional harvesting of the condensation energy from water vapour in winter [12] instead using collectors with insulation**
- **Increase the subcooling of liquefied refrigerant from typically 5°C to about 40°C**
- **Use of natural refrigerants like Propane with Global Warming Potential GWP=3 instead of Hydro Flour Carbons with GWP>1000 [5]**

The disruptive chiller process with natural refrigerant Propane (R290, GWP=3) allows in combination with the storage cascade to massively increase the subcooling of liquefied refrigerant from typically 5°C (process \{123´4´1\}) to 40°C (process \{12341\}) by sourcing the subcooling HEX with cold medium from BS3, thus avoiding flash gas formation. The energy related to \{3´3\} is stored as “valuable heat” in BS3 and helps to avoid freezing in winter. The additional cooling power \{44´\} released during evaporation can be used in applications with heat and cold demand such as supermarkets for operation of the cold chain. As the work of the compressor \{12\} remains unchanged, the net efficiency is given by \( \text{COP}_{ges} = \text{COP} + \text{EER} = (\{23\} + \{41\})/\{12\} \), which is approaching 2-digit values.

![HVACC 4.0](image1)

**Figure 5.** New building services with HVACC 4.0 (left) and the disruptive refrigerant cycle (right)
3.3 Expected results and next steps

A: Heat source “PVT-collectors + HVAC 4.0”:

Figure 6 shows estimations for the expected COP and EER under the assumptions shown on the right. Both COP and EER have been calculated straightforward by taking the enthalpy readings from the log p(h) for the assumed $T_w=T_{warm}$ (40 resp. 55°C) and $T_k=T_{cold}$ (0 resp. 15°C) and are shown in the table. For calculation of the efficiency $\eta_{HP}$ of the heat pump, the yellow marked %-values in the 3rd column have been modified until the COP resp. EER values shown in the red respectively blue circles are identical with the values from the enthalpy calculation.

It turns out, that under the given assumptions the COP can be tripled compared to the baseline “air-water heat pump”, where $T_{cold}$ has been lowered by 5°C due the phase transition air-liquid. As can be seen, the efficiency of the heat pump $\eta_{HP}$ is with values up to 70% considerably higher than the 50% value shown in Figure 1 for a best-practice water-water heat pump. This may be attributed to the facts that losses in the heat exchanger ($\Delta T_{HEX}$ in Figure 1) of the condenser and evaporator and auxiliary devices have been neglected so far.

It is planned to check the feasibility of the system and to validate the predicted COP/EER in a project by setting up and testing one or two demonstrators. The project has been applied at Projektträger Jülich within the 7th Energieforschungsprogramm der Bundesregierung with partners FhG ISE, Bartl, resenergy and easy-tnt.

B: Heat Source “Thermally activated Sheet Pile System + DG”:

The research project at RWTH for characterization of Sheet Pile Systems [9] is ongoing. A first “stand alone” demonstrator similar to that shown on the right side of Figure 4 has been set up at Hotel “Deutsches Haus” in Feldberg, Germany, where the Sheet Pile Wall is used to separate the close-by Haussee from the hotel recreation area. Measurements about performance of the system are under way.

New applications for thermally activated Sheet Pile Systems are expected if set up at flowing water like rivers for e.g. shoreline stabilization. At a heat extraction power of 1.000W/m² a 1.000m sheet pile wall with 12m depth will be able to extract 12 MW thermal energy. This will open new opportunities for operation of next generation DGs at low temperatures with RE near-surface geothermal energy instead of using high temperature waste heat from Combined Heat and Power, which are used today for operation of 3G DG (3rd generation) at $T=70…100°C$ or for 4G DG (4th generation) at $T=50…70°C$ [14]. For thermally activated Sheet Pile Systems there are basically two options: (1) Use a giant heat...
pump for realization of a medium T-lift and operate the DG at $T=30\ldots45^\circC$, which is suitable for space heating in houses with area heaters or (2) Use a giant heat pump for realization of a small T-lift for operation of a “cold DG”, also known also as an anergy network, at $T=20\ldots30^\circC$, and realize a T-lift adjusted to the needs of the building via a stand-alone heat pump as part of the building service.

3.4. Summary
New RE sources for efficient generation of “low temperature heat and cold” ($10\ldots25^\circC$) like possible with unglazed PVT-collectors and thermally activated sheet pile systems have the potential to become a gamechanger-technology for future heating and cooling in buildings, especially if combined with intelligent storage, heat pump and next generation DGs.

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Acronyms:
BS Buffer Storage
COP Coefficient of Performance (of heat pumps)
DG District Grid
EER Energy Efficiency Ratio (of chillers)
GWP Global Warming Potential (of refrigerants)
HEX Heat Exchanger (e.g. used in heat pumps like plate heat exchanger)
HVACC 4.0 Heating, Ventilation, Air Conditioning and Chilling (4.0: considering megatrends)
HVACR Heating, Ventilation, Air Conditioning & Refrigeration (state of the art as benchmark)
PV Photo Voltaic (collectors)
PVT Photo Voltaic & Thermal (collectors)
RE Renewable Energies (like ST=Solar Thermal or GT=Geo-Thermal)
TMD Temperature Modification Device (similar like water-water heat pump)
VRF Variable Refrigerant Flow (of refrigerant) in heat pumps allowing heating and cooling