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DECARBONISATION THROUGH INNOVATION

Innovative heating and cooling water terminal units for NZEB, ZEB and ZCB, designed to maximize reciclabilty of materials of energy efficient heat pumps comfort systems

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Abstract

In the future of heating and cooling comfort systems, we can expect a progression beyond the concepts of Nearly Zero Energy Buildings (NZEB), Zero Energy Buildings (ZEB) and Zero Carbon Buildings (ZCB).
As these standards focus mainly on energy efficiency and carbon emissions, future generations of heating and cooling comfort systems will likely pursue even more ambitious sustainability goals, integrating a variety of comfort solutions including integrated fresh air management, circular economy principles and holistic approaches to environmental impact, with a special focus on a more rational use of materials.
The water terminal units analysed in this paper, similar in principle to traditional fan coil units, are based on a water-to-air microchannel heat exchange technology, which is aimed not only at achieving high energy efficiency, but also to reach high level of recyclability of materials. This means that the relevant part (over 94% by weight) of the materials used in the water terminal unit described will be either renewable, reusable or recyclable.
As fan coil units are generally emerging as a very valuable emission solution for heating and cooling, water-based heat pump comfort systems, the indoor comfort terminal units described in the present paper can provide these systems with additional value related to the rational use of materials, rather than simply maximizing their energy performance.
In detail, the goal, considering the end-of-life cycle of fan coil units, is to try to eliminate waste as much as possible and keep materials in a closed loop, considering recyclability as a relevant parameter alongside energy efficiency.
As sustainability and technology continue to evolve, and considering that significant progress has already been made, for example in terms of energy-efficient heating and cooling generation (e.g., through heat pump-based solutions) and intelligent controls (e.g., Smart Readiness Indicator – EPBD [1]), the expectation is that developments related to highly recyclable indoor water terminal units can play an increasingly active role in improving water-based heat pump comfort systems in the future, also facing to conscious use of materials.
In this context, present paper focuses on the analysis of the relevant technical characteristics for indoor water terminal units used in water-based heat pump comfort systems, in order to meet the requirements of NZEB (Nearly Zero Energy Buildings), ZEB (Zero Energy Buildings) and ZCB (Zero Carbon Buildings) and to identify the most promising solutions in terms of energy efficiency and recyclability.
Considering the significant growth, expected in the coming years, for water-based heat pump comfort systems and relative fan coil units, it is very important that research could move forward not only focusing of the heat pump units (heat generation), but also taking in proper account water terminal units (heat emission).

Keywords: Recyclable HVAC; Fan Coils; Microchannel.

1. Introduction

Several experiences in recent 25 years (approx. from year 2000 to 2025) are demonstrating the concept that, to obtain buildings indoor comfort and energy saving goals, relevant actions should be done in all parts of the building with a focus on 3 main areas:

- Building Envelope
- Heating, Ventilating and Air Conditioning (HVAC) Systems
- Building Automation and Controls (BAC)

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In most cases, in fact, the best result it is not a mere simple action, for example passing from Fossil Fuels Boilers to Heat Pumps, it is more frequently a combined effect of several actions, which "mix of actions taken" may vary substantially from the different buildings and applications.

In the domain of "HVAC Systems", for example, all the parts involved it is expected they will face to a relevant change in the future, because NZEB, ZEB and ZCB are normally requiring, in general, much less energy in heating function and much more cooling energy in cooling function, with generalized increased need for ventilation, intelligent and dynamic solar shading and very accurate electronic controls.

In recent decades, in fact, according to the legislative and standards development (e.g. EPBD – Energy Performance of Buildings Directive [1]), related to building decarbonization and energy efficiency, and the consequent refinement of the construction technique of the buildings, energy efficient buildings easily will consume roughly 50% less primary energy than the current buildings and an average of also 75% / 90% (Figure 1) less than those built in the ending 30 years of the past century (approx. from year 1970 to 2000) which is a relevant part of the building stock in place.

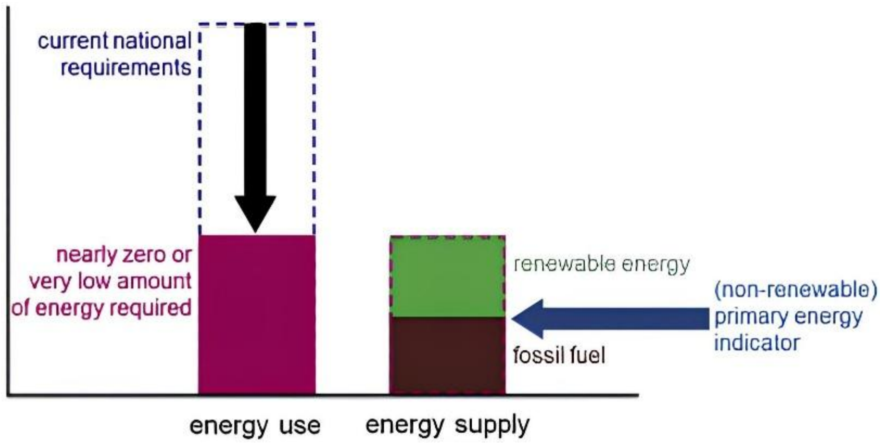


Figure 1 – Source: Concerted Action EPBD (CA EPBD) [2] Graphical interpretation of the NZEB definition according to EPBD II (Energy Performance of Buildings Directive) Articles 2 and 9, confirmed by more recent 2024 approved EPBD IV. The relevant decrease of primary energy needed to provide comfort inside energy efficient buildings due to very well insulated buildings envelope and use of renewables, is drastically influencing the characteristics of the "HVAC Systems".

1.1 Potential redundancy of functions in "HVAC Systems" and connected incoming issue of useless waste of materials.

These drastic, present and future, changes in energy demand, not only in NZEB but more and more in ZEB and ZCB, have an integrated impact on all main parts of the HVAC Systems composed of four subsystems:

1. **Thermal energy generation/transformation** (such as, non-exhaustive: heating and cooling energy generation, etc.);
2. **Distribution** network of the vector fluids (such as, non-exhaustive: water, air, refrigerant gases, etc.);
3. **Diffusion** indoor comfort terminal units (e.g. by convection, conduction, radiation, etc.);
4. **Control** and comfort management devices (such as, non-exhaustive: thermal control units, programmable thermostats, radio controllers, web controllers, IoT devices, BAC, etc.).

It is nowadays generalized opinion of the HVAC technical community that comfort systems should be in the future not only evaluated for "Comfort and Energy Savings" characteristics (as it was focus in the years from 2000 to 2025 approximately) but also for the incoming issue of rare materials usage and possible recyclability of materials and components, because: exiting from the energy dependency and entering into the raw material dependency it is not the permanent solution needed.

For example, in recent decades, in order to provide comfort and energy saving in all functions (e.g. heating, cooling, ventilation, heat recovery, etc.) and needs (e.g. large use of renewables, etc.), sometimes more systems have been involved and they sometimes provided (as partial side undesired effect) overlapping of services, which, in many cases, could generate useless waste of materials.

It is not rare, in fact, to find, for example, in a residential building simultaneous presence of: water radiator for heating in winter, ventilation and heat recovery units for IAQ and split type room air conditioners (RAC) for cooling in summer (which can provide also heating in mid seasons). This overlapping of services (e.g. you can both have heating service with boiler and radiators or using RAC in HP mode) provided with independent logics, can lead to waste of planetary resources and energy waste for fabrication, installation, maintenance and end of life recycling of those systems.

Under these circumstances, present paper is focused on studying what are the characteristics of the different types of above-mentioned "*3. Diffusion indoor comfort terminal units*" expected to be relevant in modern energy efficient heat pumps comfort systems for NZEB, ZEB and ZCB.

We will specifically focus the analysis on water based solutions, such as (non-exhaustive): heaters or radiators, heated towel rails, convector heaters, baseboard heating terminals, radiating panels (e.g. floor, wall, ceiling, etc.), fan coils, active/passive chilled beams and any new solutions available, aimed to improve comfort, decrease primary energy consumption and maximize recyclability of materials, minimizing waste of resources.

2. Challenge #1: Satisfying heating and cooling demand "new rules" of high energy efficient buildings where preferred technology, for NZEB, ZEB and ZCB, is normally based on heat pump technology

Designing for a proper indoor climate in NZEB, ZEB and ZCB, besides the superlative environmental advantage, implies several challenges.

*2.1 Analysis of "**Heating and Cooling Capacity"** required in the high energy efficient buildings*

In well-insulated buildings equipped with heat recovery, the heating system must operate on the basis of a very low average heat need while remaining reliable and energy efficient during peak load periods.

The improved thermal envelope will shorten the annual operation time, but peak load situations need to be designed very carefully to ensure adequate system capacity. Another challenge is to optimize the thermal envelope and architecture in such way that the summer cooling loads are minimized. In principle the energy use for heating and cooling should be optimized during building design. Clearly passive measures like solar shading, geometry and building orientation should of course always be exploited to a maximum, but much evidence still points to potential concrete severe overheating problems in well insulated buildings.

Often overheating is not even limited to the hot summer months. Typically, large heat gains from the sun can start to heat up a building already in March and April (Diagram 1), with a similar pattern in autumn.

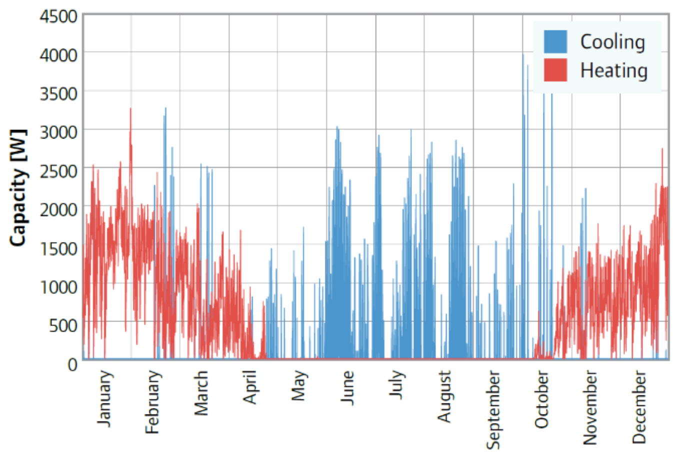


Diagram 1 – Cooling loads are present in summertime as well as throughout the intermediate seasons and this fact will require a wider elasticity and low inertia to the comfort system. Experiences from built houses and detailed building simulations calls for a careful and integrated approach when designing heating and cooling systems for NZEB. Source: REHVA Journal [3]

The heat gains entering the house as solar radiation through the windows can be several hundred W/m², largely exceeding the dimensioning heat power. The heat gains from the sun combined with the internal heat gains create a need for cooling, even in the colder seasons.

Several tendencies indicate that the need for cooling in residential buildings is generally increasing. This is partly because we experience more extreme weather types with warmer summers, because people's

requirements for indoor comfort are rising and finally because of low energy building codes with stricter requirements for tightness and insulation have brought about significant cooling loads during the warmer seasons.
Heat pump technology is widely used in low energy houses and is an important way to reduce primary energy use. The overall efficiency of heat pumps strongly depends on the supply temperature in the heating system. The lower the supply temperature, the higher the energy efficiency index (COP / EER / SCOP / SEER according to EN 14511 [4] and EN 14825 [5]).

2.2 *Analysis of "**Heating and Cooling Primary Energy and Peak Loads**", to be supplied, by indoor comfort terminal units, into in high energy efficient buildings: example of residential buildings and offices*

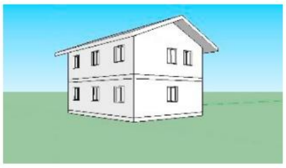
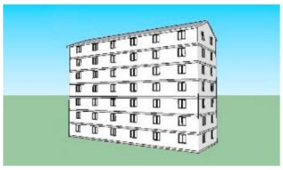
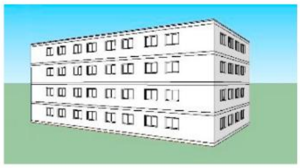
The NZEB requirements on comfort terminal units are not only related to *"Heating and Cooling Capacity"* analyzed at point 2.1, but also, they are affected by significant imbalance between space Heating and Cooling Primary Energy and Peak Loads demand.

The analysis performed by the Department of Energy of University Politecnico di Torino (Italy) [6] on three different building types (Table 1):

- Single-family house (SFH);
- Apartment block (AB);
- Office building (OB).

supposed located in Milan (2404 HDD, Italian climatic zone E) and Palermo (751 HDD, Italian climatic zone B), demonstrate how current condition of high insulated buildings can generate significant imbalance of NZEB Heating and Cooling Primary Energy and Peak Loads, that has an impact in all part of the comfort systems and in particular on comfort terminal units deputed to provide comfort inside buildings in every room/ambient.

Table 1 – Assumptions considered in the simulation, from the publication "The significant imbalance of NZEB energy need for heating and cooling in Italian climatic zones" [6]

Case study	Single-family house (SFH)	Apartment block (AB)	Office building (OB)
			
V_g [m^3]	584	8 199	6 100
V_n [m^3]	486	5 738	4 101
A_f [m^2]	162	2 125	1 519
A_{env} [m^2]	424	3 261	2 129
A_w [m^2]	20.3	275	434
A_{env}/V_g [m^{-1}]	0.73	0.40	0.35
WWR [-]	0.097	0.123	0.591

Nomenclature: V = volume [m3] g = gross n = nett
A = area [m2] f = floor env = envelop w = window
WWR = window-to-wall ratio

The residential buildings have been selected among the representative building types of the IEE Project TABULA "Typology Approach for Building Stock Energy Assessment" used for the compliance evaluations with European Directive EPBD (Energy Performance of Buildings Directive). The office building analyzed is a reference office building analyzed by the ENEA (Italian National Agency for Energy) in the definition of representative buildings for energy efficiency (Ref. ENEA RdS/2010/197) [7].

The U-values (indicating the thermal transmittance, as the rate of transfer of heat through a structure), expressed in Table 2, of the building envelope are those of the notional reference building. They differ in function of two application steps, from 2015 to 2020 and from 2021 onwards and of the 2 climatic zones.

The results indicate that the increase of the insulation layer thickness has a twofold and opposite effect. On one hand, there is an appreciated reduction in the heating demand of the building and on the other an (undesired) increase in the cooling energy needed.

All these dynamics have an impact on the indoor comfort terminal unit's capability to react to the different conditions and their sizing risk to be substantially different from Winter to Summer.

Many existing indoor comfort terminal units are designed to work with traditional balance from Winter to Summer energy needs and many of them can work improperly/inefficiently when facing NZEB, ZEB and ZCB. This will impact also on the selection of the heat pumps systems which in many NZEB, ZEB and ZCB will be largely used in the building renovation period 2025-2050.

Table 2 – Results of the analyzed configurations: net energy need (EPnd) for cooling and heating and peak power (P) of cooling and heating. Publication "The significant imbalance of NZEB energy need for heating and cooling in Italian climatic zones" [6]

Building	City	Thermal insulation position	Total solar energy transmittance (glazing + shading)		EP_{nd} [kWh·m^{-2}] Cooling ($EP_{C,nd}$ [kWh·m^{-2}])	EP_{nd} [kWh·m^{-2}] Heating ($EP_{H,nd}$ [kWh·m^{-2}])	Peak loads [W·m^{-2}] Cooling (P_C [W·m^{-2}])	Peak loads [W·m^{-2}] Heating (P_H [W·m^{-2}])
Single-family house (SFH) $A_{env}/V_1 = 0.73$ m^{-1}; WWR = 0.097	Milan	INT	0.35	U 2015	-15.62	46.12	-19.06	23.55
				U 2021	-16.53	38.13	-18.73	20.71
			0.15	U 2015	-14.17	47.69	-17.10	23.60
				U 2021	-14.91	39.70	-16.73	20.77
		EXT	0.35	U 2015	-14.88	46.24	-17.79	23.38
				U 2021	-15.63	38.05	-17.40	20.43
			0.15	U 2015	-13.42	47.84	-15.82	23.41
				U 2021	-14.04	39.68	-15.37	20.47
	Palermo	INT	0.35	U 2015	-21.66	44.33	-22.25	36.67
				U 2021	-22.81	38.16	-22.33	32.73
			0.15	U 2015	-19.51	45.56	-19.65	38.53
				U 2021	-20.51	39.39	-19.70	33.77
		EXT	0.35	U 2015	-20.14	45.07	-20.38	39.47
				U 2021	-21.26	38.89	-20.54	35.91
			0.15	U 2015	-18.02	46.33	-17.81	39.49
				U 2021	-19.02	40.15	-17.95	35.99
Apartment block (AB) $A_{env}/V_1 = 0.40$ m^{-1}; WWR = 0.123	Milan	INT	0.35	U 2015	-29.47	14.81	-14.64	12.11
				U 2021	-30.88	11.63	-14.44	10.53
			0.15	U 2015	-27.46	16.10	-13.30	12.22
				U 2021	-28.69	12.84	-13.03	10.66
		EXT	0.35	U 2015	-29.15	14.85	-13.27	12.18
				U 2021	-30.52	11.54	-13.77	10.35
			0.15	U 2015	-27.15	16.13	-12.75	12.05
				U 2021	-28.33	12.77	-12.44	10.44
	Palermo	INT	0.35	U 2015	-43.94	2.02	-18.71	8.67
				U 2021	-44.38	1.62	-18.46	7.99
			0.15	U 2015	-39.56	2.52	-16.82	9.01
				U 2021	-39.89	2.05	-16.56	8.38
		EXT	0.35	U 2015	-43.09	1.99	-17.86	8.12
				U 2021	-44.68	1.26	-17.76	6.84
			0.15	U 2015	-38.71	2.50	-16.05	8.51
				U 2021	-40.13	1.55	-15.92	7.42
Office building (OB) $A_{env}/V_1 = 0.35$ m^{-1};WWR 0.591	Milan	INT	0.35	U 2015	-40.29	19.84	-24.54	14.26
				U 2021	-42.72	14.97	-24.48	13.05
			0.15	U 2015	-37.12	21.62	-23.85	14.84
				U 2021	-39.30	16.57	-23.81	13.68
		EXT	0.35	U 2015	-40.11	19.68	-24.18	13.61
				U 2021	-42.56	14.83	-24.20	11.56
			0.15	U 2015	-36.91	21.47	-23.75	14.16
				U 2021	-39.09	16.46	-23.74	11.89
	Palermo	INT	0.35	U 2015	-59.19	4.34	-22.50	18.57
				U 2021	-60.05	3.46	-22.52	16.12
			0.15	U 2015	-53.12	5.28	-22.08	18.77
				U 2021	-53.77	4.31	-22.07	16.38
		EXT	0.35	U 2015	-58.73	4.23	-22.42	18.23
				U 2021	-61.77	2.37	-22.32	15.76
			0.15	U 2015	-52.59	5.18	-21.95	18.45
				U 2021	-55.25	3.05	-21.77	16.03

3. Challenge #2: While reaching hygro-thermal comfort and adequate indoor air quality, with energy saving approaches, requested by high energy efficient buildings: privilege the use HVAC components and products that are coming from recycled materials and that are recyclable in the end of life

Historically (approximately before the year 2000) HVAC system design was focused primarily on functional satisfaction, ensuring hygro-thermal comfort and adequate indoor air quality throughout all seasons (basically keeping mainly temperature - and occasionally R.H.% and CO_2 levels - indoor at a comfortable level or within certain acceptancy criteria). The main objective was to provide reliable space heating, ventilation and air conditioning for comfortable indoor environments for people.

Over the past two-three decades (period 2000-2025 approx.) this focus has progressively been enlarged, including energy performance optimization. Regulatory frameworks such as the Ecodesign Directive [8] and the Energy Labelling Regulations [9][10] set efficiency and performance requirements for HVAC products, while the Energy Performance of Buildings Directive (EPBD) establishes criteria for the overall building energy demand (Table 3).

Table 3 – Schematic exemplificative and non-exhaustive approach to energy efficiency in HVAC and Buildings

Scope	Key Regulation	Main Performance Indicator
Individual HVAC equipment (Products combined into Systems)	Ecodesign Directive & Energy Labelling Regulations (EU)	e.g. Seasonal efficiency (SEER, SCOP, etc.)
Building systems (HVAC + Building envelope)	Energy Performance of Buildings EPBD, RED and RES Directives	e.g. Primary energy demand (kWh/m²·year)

New approaches are in the future required also to keep care about **materials uses**: for example, copper (tube) and aluminium (fins) heat exchanger coils (Figure 2a), widely used for high-efficiency heat transfer in fan coils or chillers, require energy-intensive separation processes to recover metals. That is why whenever possible copper-aluminium coils have been substituted by microchannel heat exchangers (Figure 2b) in several applications. This is the case of most part of condensing coils of chillers that in recent 10 years (approx. from 2015 to 2025) have passed approximately in 70/90% of the cases form Cu-Al to Microchannel Aluminium Coils, that are made only with aluminium with extremely lower problems with end of life recycling.

Regarding heating and cooling water terminal units (e.g. traditional fan coil units, convectors, chilled beams, etc.) present metal components (e.g. Cu-Al coils, steel casings, etc.) and polymer-based components (e.g. insulation, gaskets, etc.) contribute significantly to embodied energy and pose challenges for end-of-life recycling due to material heterogeneity, considering for example EN 15978 [11].

Figure 2a – Typical Copper–Aluminum Tube-and-Fin Coil

The traditional copper–aluminum tube-and-fin heat exchanger consists of extruded copper tubes inserted into a finned pack made of aluminum.

The recyclability of this type of coil involves more complex processes compared to single-material heat exchangers, as the separation of copper and aluminum requires additional mechanical or chemical treatment steps.

Moreover, copper is increasingly considered a strategic and high-value material, with growing demand from sectors such as electric vehicles and renewable energy technologies. Consequently, its use in HVAC applications is becoming less sustainable from both economic and environmental perspectives.

According to the principles outlined in EN 15978, which emphasizes material efficiency and end-of-life recyclability as key indicators of environmental performance, the use of multi-material assemblies such as Cu–Al coils result in a less favorable life cycle profile of recyclability.

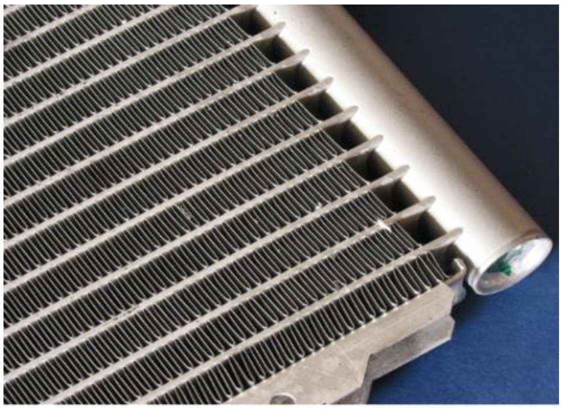


Figure 2b – Typical Microchannel Aluminum Heat Exchanger

The microchannel heat exchanger (MCHE) features a monolithic, all-aluminum construction, which simplifies recycling and enhances material circularity.

Its high heat transfer efficiency, lower material mass, and full aluminum composition make it a more sustainable and resource-efficient alternative.

In line with the sustainability criteria of EN 15978, the microchannel coils use in HVAC products offers clear advantages in terms of recyclability, embodied energy, and end-of-life recovery potential.

As a result, this technology has become the preferred choice for condensers (using natural or synthetic refrigerant, dual phase fluids) and free coolers (glycolic water, single phase fluids) in modern chillers.

In the automotive industry, microchannel aluminum heat exchangers have entirely replaced Cu–Al coils over the past two decades due to their superior performance, lighter weight, improved environmental profile and recyclability.

3.1 Hypothesis of "Evaluation Criteria" of "Diffusion indoor comfort terminal units" used in "water-based heat pump comfort system" for future energy efficient buildings using recycled and low quantities of scares material resources

According to the relevant characteristics cited in Chapter 3 (Satisfying heating and cooling demand "new rules" of high energy efficient buildings) and Chapter 4 (Privilege the use HVAC components and products that are coming from recycled materials and that are recyclable in the end of life), in present paper it has been elaborated a system of 9 criteria of evaluation that takes into account, for *"water-based heat pump comfort system*" with special focus on *"Heating and cooling water terminal units under NZEB, ZEB and ZCB circumstances"*, what could be the good characteristics that can maximize long term value in energy efficient heat pumps comfort systems, including recyclability.

Table 4 below explicitly links each evaluation criterion for water indoor comfort terminal units, in a qualitative estimation, to the corresponding energy performance requirements outlined in EN 14511 [4] and EN 14825 [5] for heat pumps, as well as to the sustainability principles and life cycle stages defined in EN 15978 [11].

Table 4 – Criteria from 1 to 9 of evaluation of terminal units for future energy efficient buildings

No.	Evaluation Criteria in Air To Water Heat Pumps Comfort Systems	Impact characteristic of Water Indoor Comfort Terminal Units	Relevance to NZEB / ZEB / ZCB and EN14511 and EN14825	Reference to EN 15978 Life Cycle Aspects and Recycling
1	Dual heating and cooling capability	Indoor water terminal units must provide both heating and cooling to cover annual thermal comfort requirements with a single device.	Enables simplification of systems, reduction of embodied materials, and better operational energy balance.	*Modules B1–B7 (Use stage):* improved operational efficiency and reduced energy demand.
2	Operation with moderate water temperatures	Preference for units operating with water at moderate temperatures (≈35–30 °C for heating, 18–23 °C for cooling).	Increases the seasonal efficiency of heat pumps (SCOP, SEER) and supports renewable energy integration.	*Module B6 (Operational energy use):* lower energy consumption and higher system efficiency.
3	Integrated functions (heating, cooling, ventilation, purification)	Units integrating air renewal, filtration, and purification minimize the need for separate systems.	Reduces total system components and embodied impacts while improving indoor air quality and comfort.	*Modules A1–A3 (Product stage) & B1–B5:* lower material input and better user comfort performance.
4	Low thermal inertia	Units should react rapidly to changes in demand, minimizing comfort fluctuations.	Critical for dynamic operation in NZEBs and spaces with variable occupancy.	*Module B1 (Use stage):* ensures consistent indoor environmental quality and energy control.
5	Fast ramp-up capability	The ability to quickly reach comfort conditions after standby or intermittent use.	Reduces unnecessary pre-conditioning energy and supports smart control strategies.	*Module B6:* enhances energy management and reduces transient losses.
6	Uniform air diffusion and absence of stratification	Heat distribution must avoid hot/cold spots or air drafts that reduce comfort.	Ensures compliance with indoor environmental quality requirements for NZEB/ZEB standards.	*Module B1:* contributes to occupant comfort and indoor environmental performance.
7	Compactness and aesthetic integration	Units should minimize occupied space/volume needed for HVAC devices and integrate seamlessly with interior design.	Maximizes usable space and architectural flexibility, important in high-performance buildings.	*Modules A1–A3:* reduction of material use and improved adaptability (Module B5).
8	Use of recycled / recyclable materials	Preference for materials with high recyclability and certified recycled content.	Supports circular economy objectives and reduces embodied carbon footprint, essential for ZCBs.	*Modules A1–A3, C1–C4, D:* improved end-of-life recovery and material efficiency.
9	Ease of cleaning and maintenance	Surfaces must allow easy user-level cleaning to maintain hygiene and system efficiency.	Ensures indoor air quality and minimizes environmental impact of maintenance.	*Modules B2–B5:* reduced resource consumption and healthier indoor environment.

4. Typologies of the most diffused heating and cooling water terminal units in Europe

In Europe (differently from many countries in the Asia that use normally split type room air conditioners (RAC) in heat pump version and from American countries which use traditionally more air side systems) there are several diffusion indoor comfort terminal units on the market that use air and water as vector fluids to transport energy into the different indoor environments.

Their vast diffusion occurred in successive stages, starting from radiators, where the water supply temperature varies between 65°C (in the most recent radiators systems) and 80°C (typically in systems prior to 1950/70). The water normally returns to the generator with approximately 10 - 20°C less.

Nowadays many other diffusion indoor comfort terminal units (also using low water temperature in winter such as 30-35°C) have been introduced and the types (non-exhaustive) analyzed in present paper are:

(A) Radiators (Figure 3)
(B) Decorative radiators (Figure 4)
(C) Convector heaters (Figure 5)
(D) Baseboard terminals (Figure 6)
(E) Radiant Solutions (Figure 7)
(F) Fan Coils (Figure 8)
(G) Ultrathin Fan Coils (Figure 9)
(H) Active/Passive chilled beams (Figure 10)
(I) Microchannel Fan Coils (Figure 11)

To better understand their segmentation, the above 9 types of diffusion indoor comfort terminal units, have been divided into 3 main categories, segmented in the following points 4.1 – 4.2 – 4.3 as:

- Traditional “heating only”
- Traditional “heating and cooling”
- Multipurpose “heating, cooling and fresh air renewal and purification"

*4.1 Traditional typically **“heating only”** indoor comfort terminal units*

(A) Radiators

Figure 3 – Images for pure illustrative purposes, non-exhaustive, of several types of radiators widely diffused for heating only application using water as thermal vector to provide comfort in winter inside buildings.

(B) Decorative radiators

Figure 4 – Image for pure illustrative purpose, non-exhaustive, of a typical radiator normally used for bathrooms: very widely diffused for heating only application using water as thermal vector to provide heating function in winter season inside buildings.

(C) Convector heaters

Figure 5 – Image for pure illustrative purpose non-exhaustive, of a typical convector normally used for large spaces: very widely diffused for heating only application using water as thermal vector generating localized convection flows of air indoor, normally without filtering function.

(D) Baseboard terminals

Figure 6 – Image for pure illustrative purpose, non-exhaustive, of a typical baseboard heating stripes quite low diffused in the past for heating only application using water as thermal vector generating quite uniform distributed convection flows of air indoor.

4.2 Traditional ***"heating and cooling"*** *combined comfort terminal units*

(E) Radiant Solutions

Figure 7 – Image for pure illustrative purpose, non-exhaustive, of very widely diffused solutions for radiant sensible only heating (from left to right: floor, wall and ceiling applications) and, in a few cases, also for sensible only cooling: application reached using water at moderate temperatures (e.g. 18-23°C in summer / 35-30°C in winter) as thermal vector to provide heating in winter season and cooling in summer season inside buildings. Dehumidification in summer in this last case have to be provided with dedicate system.

(F) Fan Coils

Figure 8 – Image for pure illustrative purpose, non-exhaustive, of very widely diffused solutions for forced air convection (from left to right: floor standing application with casing, recessed version without casing and underfloor solution) for heating and cooling application using cold or hot water as thermal vector to provide heating function in winter season and cooling function in summer season. Using normally water at 7-12°C in summer and 45-40°C in winter, they not always are able to guarantee best overall performances at heating and cooling generation side (e.g. SEER and SCOP, when combined with Heat Pumps).
Winter comfort is also a relevant concern due to air speed and stratification..

(G) Ultrathin Fan Coils

Figure 9 – Image for pure illustrative purpose, non-exhaustive, of very widely diffused solutions for forced air convection (from left to right: ultrathin floor standing application with casing and with additional integrated radiant heating function) for heating and cooling application using cold or hot water (e.g.7-12°C in summer and 45-40°C in winter) as thermal vector to provide heating in winter season and cooling in summer season. The radiant heating function helps improve the heating comfort compared to traditional Fan Coils.

4.3 *Multipurpose comfort terminal units able to provide in one single unit* ***"heating, cooling and fresh air renewal and purification solutions"*** *quite often equipped with integrated CO_2 and VOC controllers*

(H) Active/Passive chilled beams

Figure 10 – Image for pure illustrative purpose, non-exhaustive, of very widely diffused solutions (especially in northern Europe) for chilled beams (from left to right: active type with also air renewal and purification integrated supply from central AHU / HRU and passive type) for heating (and, in many cases, also cooling) application using water at moderate temperatures (e.g. 18-23°C / 35-30°C) as thermal vector to provide heating function in winter season and cooling function in summer season.
As they work only in sensible cooling and heating these units are able to substantially contribute to superlative seasonal energetic performances (e.g. SEER and SCOP) on heating and cooling generation side when, for example, used in combination with reversible heat pumps. Excellent results in the control of IAQ (Indoor Air Quality) with one single indoor terminal unit.
This solution is a bit penalized for the large surface needed and for the ceiling position which is mandatory for such units.

(I) Fan Coils with microchannel heat transfer technology and polystyrene mold specific for HVAC uses, with 94% (in weight) of recycled and recyclable materials.

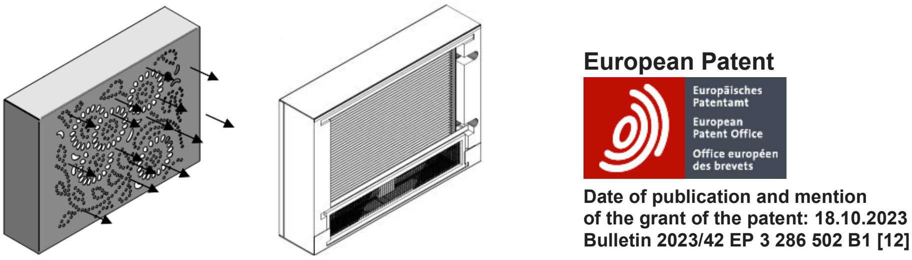


Figure 11 – Image for pure illustrative purpose, non-exhaustive, of Fan Coils with microchannel heat transfer technology [12]

5. Additional considerations related to the impact of microchannel aluminum exchangers in water to air configuration for emitters and in refrigerant to air configuration for Heat Pumps in HVAC

Fan Coils with Microchannel Technology can be designed for heating and cooling application using water at different temperature as thermal vector to provide heating function in winter season and cooling function in summer season. As it can work in sensible cooling and heating too (eliminating therefore the need for drain pan and drainage network, like a chilled beam, at moderate water temperatures e.g. 18-23°C / 35-30°C) this microchannel solution advantage in sensible heating and cooling performance versus fin and tube solutions, can be qualitatively summarized as follows in Table 5.

Table 5 - Sensible Cooling Performance (non-exhaustive) comparison based on 3 row Fin & Tube coil (16 FPI) Vs. 25mm Microchannel Coil (21 FPI)

Metric	**Fin & Tube** 	**Microchannel** 	**Improvement** **Microchannel** **Vs Tube & Fin**
(A) Sensible heat from air (Temperature reduction only, no moisture removal) Sensible capacity [parametric]	1.0	1.15 – 1.40	**+15/+40%**
(B) Air-Side Heat Transfer Coefficient h_air [parametric]	1.0	1.3 – 1.6	**+30/+60%**
(C) Sensible cooling capacity per unit coil volume. Power density [parametric]	1.0	1.5–2.5	**+50/+150%**

The use of microchannel heat exchangers in place of traditional Tube & Fin solutions for sensible only applications thanks to heat transfer efficiency, lower material mass and full aluminium composition can offer several advantages, still not yet fully adopted from the fan coils sector (differently from Chillers and Automotive that are largely using such microchannel technology).

Differently from all other terminal units described, these units are mainly composed by aluminum and polystyrene (94% in weight) which are highly recyclable, reaching good positioning in terms of EN 15978, mainly because of the following reasons:

1. **Aluminum** has a well-established recycling pathway. At end of life, aluminum components can be easily separated and sent to recycling facilities, where they are remelted and reintroduced into the production cycle. Aluminum recycling is highly efficient, requiring significantly less energy than primary aluminum

production, and can be repeated multiple times without loss of material properties. In EN 15978 terms, this contributes positively to Modules C3 (waste processing) and D (benefits and loads beyond the system boundary) through high recycling rates and substantial avoided impacts.

2. **Polystyrene** can follow different end-of-life routes depending on local waste management infrastructure. Ideally, it is collected separately and recycled either mechanically (granulation and reprocessing into new plastic products) or chemically (depolymerization into monomers or feedstock). When recycling is not available, energy recovery through controlled incineration is a viable alternative, as polystyrene has a high calorific value. Landfilling represents the least favorable scenario and should be minimized in line with circular economic principles.

Overall, the high share of recyclable materials enables:

- **Low impacts in Module C1–C4** (deconstruction, transport, waste processing, and disposal),
- **High recovery potential in Module D**, thanks to the substitution of virgin aluminum and plastics,
- **Good alignment with EN 15978**, supporting a circular end-of-life strategy with high material recovery rates and reduced environmental burdens.

Regarding reversible heat pump coils, several new solutions are also exploring the use of microchannel technology for reversible coils with the aim of substituting Cu-Al traditional coils, which are in general more expensive [in the Economic Value / k comparison) and in general less easily recyclable.

For example, a new type of construction that allows the coil to be defrosted more easily, while still at an early stage of adoption and testing (prototype level), is attracting increasing attention. Examples include the solution shown in Figure 12 (a patented [13] solution by Climetal SL, Madrid, Spain) and the one shown in Figure 13 (a solution developed by Kaltra, Germany).

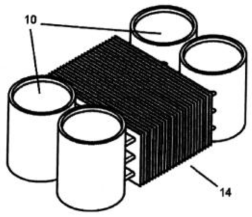


Figure 12 – Image (non-exhaustive) from the patented solution by Climetal SL, Madrid, Spain, titled Microchannel Evaporator/Condenser for Heat Pumps WO2012/072836 A1

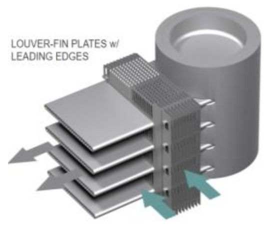


Figure 13 – Microchannel coils for air-source heat pumps. Image (non-exhaustive) from Kaltra, Germany, website https://www.kaltra.com/single-post/2021/01/18/air-source-reversible-heat-pump

These designs aim to improve defrost performance, reduce frost accumulation and enhance heat transfer efficiency during heating operation. Microchannel heat exchangers seem very promising on heat pumps condenser/evaporators in order to provide a more uniform refrigerant distribution and reduced thermal mass, which may facilitate faster and more efficient defrost cycles. As a result, these solutions may contribute to improved seasonal performance and lower energy consumption of reversible heat pump systems.

6. **Balanced scorecard to evaluate the best fitting heating and cooling water terminal units for NZEB, ZEB and ZCB requirements to maximize energy efficiency in heat pumps comfort systems and recyclability of materials expected to be more and more used in HVAC in 2025-2050 period**

Considering the different characteristics of the 9 categories of indoor water terminal units described in Chapter 5 and evaluating them with the 9 evaluation criteria defined in Chapter 4, when possible we considered quantitative KPI evaluations connected to EN 14511 [4], EN 14825 [5] and EN 15978 [11], when not possible to establish a proper KPI we used qualitative metrics in a balanced weighting from 1 to 10 points was applied to each 1-9 criterion and each 9 types of terminal unit.

Table 6 – Balanced scorecard of evaluation of water terminal units for future energy efficient buildings with heat pump comfort systems

CRITERIA	Traditional (normally) "Heating only" indoor				Traditional "Heating and Cooling"			Innovative "Heating, Cooling and Fresh Air Renovation"	
	(A) Radiators	(B) Decorative Radiators	(C) Convectors	(D) Baseboard terminals	(E) Radiant Solutions	(F) Fan Coils	(G) Ultrathin Fan Coils	(H) Chilled Beams	(I) Microchannel Fan Coils
1	5	5	5	5	10	10	10	10	10
2	2	2	2	2	10	5	5	10	10
3	2	2	2	2	5	5	5	10	10
4	8	8	8	8	4	10	10	8	8
5	6	6	8	5	2	10	10	8	8
6	5	8	5	8	10	5	7	7	7
7	6	7	6	5	10	6	8	6	8
8	8	8	6	6	8	6	6	6	8
9	6	8	5	5	10	5	5	5	6
Total Balanced Scorecard [Points]	**48**	**54**	**47**	**46**	**69**	**62**	**66**	**70**	**75**

Qualitative criteria of association of points

Points from 1 to 3	**Poor**
Points from 4 to 6	**Sufficient**
Points from 6 to 9	**Good / Very Good**
10 Points	**Excellent**

The analysis conducted on all relevant aspects mapped in the present paper regarding energy efficiency, functionality, hygienic and materials sustainability requirements of NZEB, ZEB and ZCB related to indoor comfort terminal units, produced the results in table 6, with basically 3 main levels of classification:

- LOW FITTING: Heating only terminal units are getting low levels of fitting to NZEB, ZEB and ZCB requirements, as they need auxiliary products to provide cooling and ventilation. They have in general good scoring in recyclability.

- AVERAGE FITTING: Heating and cooling solutions are getting to average levels of fitting as they need auxiliary products and plants to provide ventilation in NZEB, ZEB and ZCB. Depending on the case they can have problems of low or high inertia or stratification problems in heating in winter season, some issues on SEER and SCOP in heat pump systems, when fan coils cannot use moderate water temperatures.

- GOOD FITTING: The best-performing solutions are those that deliver high efficiency in heat pump water-based comfort systems, integrating heating, cooling and air renewal within a single unit. These systems maximize overall efficiency while minimizing material use. The highest performance levels were achieved by chilled beams and fan coil units featuring microchannel heat transfer technology.

Conclusions

Indoor comfort terminal units used in water-based Heat Pump Comfort systems will probably see, in the coming years, a substantial evolution, privileging solutions that could simultaneously:

1. Provide "all-in-one" Heating, Cooling, Air Renewal and Purification, in order to:
- fulfill complete user functionality needs;
- decrease HVAC installation complexity;
- reduce, if not eliminate, HVAC plant redundancy arising from the use of different technologies for similar services;

2. Efficiently use water at moderate temperatures (e.g., **30–35 °C in winter / 18–23 °C in summer**) in order to:
- offer a good response in terms of energy saving when used in combination with low primary-energy generators such as air-to-water heat pumps;
- provide better comfort to users due to moderate-temperature heat exchanges;

3. Allow easy cleaning and sanitization directly by end users, and not only by specialized HVAC cleaning personnel, so that indoor comfort terminal units can be sanitized as a standard operation in daily or weekly maintenance, similarly to other indoor environment components that can be easily cleaned and sanitized;

4. Be made with the largest possible share of recycled and/or recyclable materials, while ensuring the best available performances according to EN 15978, the European standard specifying the method for assessing the environmental performance of buildings using Life Cycle Assessment (LCA).

All these aspects could contribute to achieving the energy efficiency, functionality, hygiene and sustainability requirements, including the recyclability of HVAC components, of NZEB, ZEB and ZCB buildings, with an increasing application of heat-pump-based comfort systems.

Microchannel heat exchange technology has become, over the last ten years, the preferred choice for cooling-only chillers and free coolers, for several reasons related to energy efficiency, cost reduction and recyclability. Recent developments of this technology appear to offer interesting application possibilities also in the field of fan coil units, using water-to-air microchannel heat exchanger technology.

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