EPBD 2023, F-GAS 2024, Eco-design and safety standards: which design margins to be compliant with? An assessment of heat pumps for cooling

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Abstract. To decarbonize Europe achieving almost zero emissions in 2050, more stringent regulations are going to be applied. Particularly, Europe is investing in the emissions' re-duction of buildings (existing and new ones), and strong improvements in energy performance of building are expected according to novel energy performance of building directive (at last phase of negotiation). At the same time, the production and use of fluorinated gases will be further reduced with the novel F-Gas regulation (under Parliament approval). New F-Gas will affect remarkably the small size, air-to-air split systems for air-conditioning, since no fluorinated gases will be used after 2035, forcing manufacturers to the use of natural refrigerants. Being propane the most efficient among the non-toxic natural refrigerants, less refrigerant would be charged into systems according to current safety standards: this would potentially reduce the heat transfer surfaces and, consequently, for the same capacity, the energy efficiency or, for the same efficiency, the capacity would decrease. In this paper, some scenario analyses, complying with actual and future plausible dispositions, are presented, in order to showing the margins for de-sign and commenting criticalities. In particular, the optimal design options are proposed for different fluids, in terms of costs vs energy performance, under representative cases, in terms of weather conditions and building types in Italy (existing ones and new ones respecting high-efficiency standards, trying to meet the requirements of hypothesized national law following the draft of the novel EPBD).

Keywords: EPBD 2023, F-GAS 2024, electric heat pumps, design optimization, safety and comfort

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1 . Introduction

The last 20 years have been characterized by a growing awareness of climate change, global warming, and all the consequences that come with it, and therefore the need to adopt strategies to mitigate it. The objectives at the heart of the discussions, since the end of the 20th century, are the containment of the average temperature of the earth's surface with the control and reduction of greenhouse gas emissions, and therefore the reduction of energy demand. All the high-energy-intensive sectors are involved in the processes of energy transition and decarbonization. Among these, the building sector, with a total energy demand of 133 EJ in 2022 [1], accounts for 30% of the global energy demand [2].
Worldwide, this sector has been characterized, in the last 20 years, by a succession of legislative and technical measures to reduce GHG emissions, increase the energy efficiency, and the energy conversion from renewable sources. At the EU level, the first and significant European action was implemented through the Directive 2002/91/EC, Energy Performance of Building Directive (EPBD), following the 1997 Kyoto Protocol. This directive, transposed in Italy starting with the Legislative Decree 192/2005, introduced a methodology for calculating the integrated energy performance of buildings, the minimum energy performance requirements, and the energy certification of buildings. Really, in Italy, already with laws L. 373/76 (following the Kippur war) and mainly with the L. 10/91, a deep attention has been drawn to the construction sector, by introducing the first indications about thermal insulation to contain the demand for energy and use it rationally.
In 2010, a new version, the Directive 31/2010/CE (namely, the EPBD Recast), replaced that of 2002 and introduced the standard of "nearly zero-energy building" making it compulsory for all new buildings from 2019/2021, for the public and private sectors, respectively. This has been transposed in Italy with Law 90/2013, and in June 2015, three Ministerial decrees completed the regulatory framework, by defining the minimum energy requirements, and the methodology for energy certification.
Some years later, to meet the 2030 targets, the novel EU Directive 2018/844 has been published, which highlights the need for a deep renewal of the existing building stock. The latter also plays a key role in the package "Fit for 55" of 2021 which led to the latest and recent revision of the EPBD in March 2023, definitely approved only some weeks ago, in December 2023, after a long trialogue phase among Commission, Council and EU Parliament. To reduce $CO_{2\text{-eq}}$ emissions by 55% by 2030 and reach climate neutrality by 2050, the built environment must be completely decarbonized. New buildings must be zero-energy emissions by 2027 and 2030, respectively for public and all other buildings, and the existing ones must respect the minimum energy performance requirements. In detail, residential buildings must be in energy Class E by January 2030 and in Class D by January 2033 [3]. For non-residential and public buildings, the same targets have to be anticipated.
In Italy, according to the annual report on the energy certification of buildings produced by ENEA in 2023 [4], about 75% of buildings were built before 1990, and about 60% fall into the lowest energy classes, namely G and F. This scenario is fully representative of that at the European level, and therefore significant actions are needed to meet European objectives and to increase the turnover rate of the building sector, which is very poor, around 0.6%/year at EU-27 level.
Decarbonization requires a gradual transition from fossil fuels to renewable sources [5], [6], and this will lead to an electrification of all the energy sectors such as the building one. In this future scenario, in addition to the need of reducing the final usage of energy consumption in buildings, an increase of efficiency in energy consumption can be achieved through the employment of heat pumps (HP) [7], with a current number of units which is largely increasing in Europe [8]. In this field, several regulations have been adopted in order to limit the environmental impact. Among these, the new F-gas 2024 regulation [9], in force replacing

the EU Regulation 517-2014 [10], will furtherly reduce the usage of high GWP refrigerants in all the refrigeration and air-conditioning sectors. Particularly, in air source split air-conditioners and heat pumps with capacities lower than 12 kW, fluids with GWP higher than 150 will be banned after 01/01/2029, leading to the employment of transitional solutions such as the refrigerant blends R454C and R455A (both GWPs=146) as a replacement of the commonly used R32 (GWP=675). Moreover, all the fluorinated gas will be banned after 01/01/2035, therefore after that date only natural fluids such as propane and iso-butane (both GWPs=3) will be considered. Due to the flammability issues of these fluids, new design constraints must be adopted for safety reasons, as fixed by the EN-378:2016 [11] in which the maximum refrigerant charge amount that can be contained in heat pump and refrigeration systems for A3 and A2L refrigerants is evaluated depending on the floor area in which the refrigerant is supposed to be dispersed. This can bring to a reduction in performance of systems employing natural refrigerants compared with the R32 ones commonly developed in the actual market, leading these systems to not satisfy the minimum performance fixed by the Eco-design Regulation (2016/2281) [12].
In this sense, there are no other works in the literature which deal with the consequences of new building regulations and the limitations of high GWP refrigerants in Europe on the design of new heat pump systems. Therefore, this paper analyzes the design of heat pumps in cooling mode in Italy for mild and warm climate conditions, equipped on existing and future buildings according to EPBD regulations, and evaluates the optimal achievable performances in terms of investment costs and energy efficiency ratio for different refrigerant fluids, taking into account all the bans and limitations imposed by the F-gas regulation.

2 Numerical models: engineering references and space heating and cooling loads of example buildings

In this section, the employed materials and methods for the building energy simulation are described. Then, the building types under investigation are firstly characterized and then modeled, according to the points of view of architectural design and energy efficiency level. Finally, through transient energy simulation, space heating and cooling loads are evaluated hourly, by reporting the seasonal peaks.

2.1 Materials and Methods

To assess the heating and cooling power requirements reliably, after the accurate modeling of the investigated buildings, dynamic energy simulations have been conducted. The geometry of the building, the thermo-physical peculiarities of the opaque and transparent building envelopes, and the intended uses are defined in DesignBuilder®, a graphical interface of EnergyPlus [13], one of the most authoritative and widespread calculation engines for building energy simulation. The whole energy simulation program, according to the kind of study, the need of calculating the thermal filed into the building components, the computation effort, and the reliability of the simulation, allows many calculation algorithms. In this study, based on the methods available in EnergyPlus software, the transient heat transfer through the building envelope has been evaluated using the CTFs, namely the Conduction Transfer Function (CTF) method. Briefly, the HVAC (Heating, Ventilation, and Air Conditioning) system should balance the convective internal loads, the convective heat exchange from the zone surfaces, the heat transfer from air mixing between internal zones, and external infiltration. The indoor surface temperature, involved in that balance, is affected by the heat transfer from the building components, and so the heat transfer by long- and short-wave radiation, solar flux, by convection with the inside and outside air, and by conduction through the envelope components. This last contribution is linearly associated with current and previous temperatures of the internal and external surface and previous thermal flows through the CTF coefficients, evaluated employing the State Space Representation [14], defined by two linear matrixes [15]. The method allows the evaluation of the thermal field, and so the heat flux (output) as a function of the environmental temperatures (input) by neglecting the nodal temperatures, and thus the full description is obviously available in the EnergyPlus Documentation (2023) [13].

2.2 Case studies: architectural and building typology

The choice of the buildings under investigation stems from the analysis of the European project "TABULA" (Typology Approach for Building Stock Energy Assessment), in which for 21 countries a typological classification of existing buildings (mainly residential) is collected. The buildings are divided by period of construction and size. While the range for the period of construction can vary between countries, the size of the buildings is in common, in detail the following options are provided: single-family house, terraced house, multifamily house, and apartment block (TABULA WebTool [16]). In this paper, the extreme size-types have been considered, in terms of the absolute dimensions of the edifices and the values of S/V, namely the surface-to-volume ratio: the single-family house and the apartment block (Fig. 1).

Fig. 1. Example of the representative buildings: single family house (A) and apartment block (B).

Space heating and cooling needs and the peak loads of these two representative buildings are evaluated in three different climatic conditions. As it is well known, the Italian territory is divided - according to DPR 412/93 [17] - into six climatic zones, on the basis of the heating degree days (HDD, baseline 20 °C), which express the coldness of the climate. For each zone, the Decree defines the date of switching on and off of heating systems, and the maximum number of daily hours in which the winter heating can be used as well. On the other hand, there are no mandatory regulations concerning the use of cooling systems in the summer season. In this study, a warm, a mild, and a cold climate are selected, which correspond to zones B (Messina, 707 Kd), D (Genova, 1435 Kd), and F (Tarvisio, 3959 Kd), and the heating and cooling availabilities are shown in Table 1. Really, the warm-er climate belongs to climate zone A, but only two municipalities belong to this zone, so for greater representativeness of Italian territory zone B has been chosen.
The two buildings are modeled in DesignBuilder® (Fig. 2) (*version 6.1.8.021*), and five periods of construction, corresponding to five building envelope technologies (→ and so five energy efficiency levels) are considered. In detail:

- masonry (< 1940),
- reinforced concrete (1955-1970),
- reinforced concrete (according to the Law 373/76),
- reinforced concrete according to EPBD 2010,

- EPBD 2023 buildings (i.e., it has been supposed a further restriction of thermal transmittance values – U-value – around -30% compared to EPBD 2010).

The thermal characteristics for each technology, concerning the opaque and transparent building envelope, are listed in Table 2 and are settled in the DesignBuilder environment. The intended use of the buildings is residential, and all main other data – i.e., internal gains, info and boundary conditions, heating and cooling setpoints – required for the simulation of the energy needs, are listed in Table 3.

Table 1. Heating and cooling availability for the investigated climate zones.

	Heating Availability		**Cooling Availability**	
Zone B	December 1 – March 31	8 hours per day	June 1 – September 30	12 hours per day
Zone D	November 1 – April 15	12 hours per day	June 15 – September 15	10 hours per day
Zone F	October 1 – April 30	16 hours per day	June 15 – September 15	8 hours per day

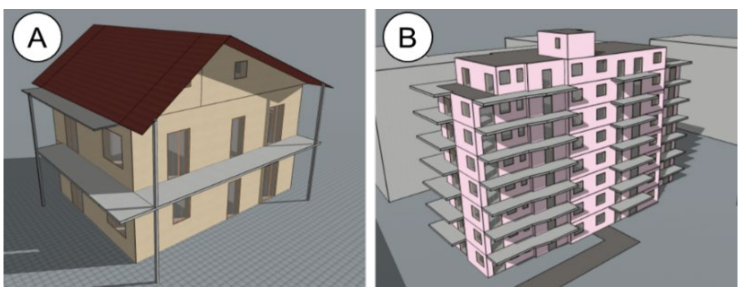

Fig. 2. Model of the buildings in DesignBuilder®: single family house (A), apartment block (B).

Table 2. Thermal transmittance values for building envelope components

	U-value walls [W/m²K]			**U-value roof [W/m²K]**			**U-value floor [W/m²K]**			**U-value windows [W/m²K]**		
	Zone B	Zone D	Zone F	Zone B	Zone D	Zone F	Zone B	Zone D	Zone F	Zone B	Zone D	Zone F
Masonry < 1940		1.60			1.80			1.70			5.70 Infiltration rate 0.7 h^{-1}	
RC 1955-1970		1.20			1.20			1.70			5.70 Infiltration rate 0.7 h^{-1}	
RC 373/76	1.10	0.72	0.60	0.87	0.65	0.50	1.10	0.72	0.60		3.2 Infiltration rate 0.5 h^{-1}	
RC EPBD 2010	0.43	0.29	0.24	0.35	0.26	0.20	0.44	0.29	0.24	3.00	1.80 Infiltration rate 0.3 h^{-1}	1.10
RC EPBD 2023	0.30	0.20	0.17	0.25	0.18	0.14	0.31	0.20	0.17	2.10	1.26 Infiltration rate 0.3 h^{-1}	0.77

Table 3. Data for the simulation of the energy needs

Building Geometry			
Single family house (SFH)		**Apartment block (AP_B)**	
Total building area [m²]	231	Total building area [m²]	3123
Net Conditioned Building Area [m²]	202	Net Conditioned Building Area [m²]	2844
Gross Roof Area [m²]	94	Gross Roof Area [m²]	400
Total building height [m]	9.9 (max)	Total building height [m]	25.6
Heating and cooling setpoint			
Space Heating setpoint [°C]	20	Space Cooling setpoint [°C]	26
Internal gains			
Occupancy rate [person/m²]	0.04	Lighting system power density [W/m²]	3
Electric equipment power density [W/m²]	4	Control: according to the daylight illuminance	
Simulation data			
Solution algorithm		Conduction Transfer function	
Surface Convection Algorithm – inside		TARP	
Surface Convection Algorithm – outside		DOE-2	
Time Step per hour		6	

2.3 Space heating and cooling power requirements at the peaks

Combining all the data discussed in the previous sub-section – building types, climate zones, and energy efficiency levels – 30 models are counted. For each model, a dynamic energy simulation is carried out in EnergyPlus (*version 9.1.0*), with the aim to evaluate the heating and cooling thermal needs, and the power requirements in the different climatic conditions and energy efficiency levels. The results for single-family houses and apartment blocks are shown in Table 4 and Table 5, respectively. In detail, the thermal energy demand (TED) for space heating and cooling, the heating and cooling peak values evaluated in the year-round simulation, and the corresponding values for sizing, considering an increase of 25% (i.e., to consider any over-power at starting point or more critical operating conditions) are analyzed. criticality in the summer season, and thus concerning the power in the cooling mode. This does not happen for cold climates, where an almost equivalent weight is obtained for the thermal energy demands in the two seasons and, for this reason, such weather will be not deepened in the following of the paper, being not critical for what concerns the sizing of HP equipment. If the attention is focused on new and/or refurbished buildings - built or subject to major renovations by the directives EPBD 2010 and EPBD 2023 – it emerges a great criticality in the summer season, and thus concerning the power in the cooling mode. This does not happen for cold climates, where an almost equivalent weight is obtained for the thermal energy demands in the two seasons and, for this reason, such weather will be not deepened in the following of the paper, being not critical for what concerns the sizing of HP equipment.

All told, to achieve meaningful outcomes and to satisfy the targets set at the European level – complete decarbonization of the building sector by 2050 – the actions of increasing the turnover rate of the existing building stock with the strong improvement of thermal and energy performance will be imperative.

Just to understand how some technologies may have positive impacts along the cooling season, as a solution to limit the cooling energy need (also promoted by the law, through tax deductions), some simulations, in the mild climate, have been again performed with the application of shading systems, externally positioned and with an activation for a solar setpoint on the fenestration of 150 W/m², during the cooling period. The savings on the peak power for the sizing are summarized in Table 6.

Table 4. Results of the analysis for single family house.

SINGLE FAMILY HOUSE								
	TED_h	TED_c	$\dot{Q}_h$	$\dot{Q}_c$	$\dot{q}_h$	$\dot{q}_c$	$\dot{q}_{h,sizing}$	$\dot{q}_{c,sizing}$
Warm Climate	[kWh_{th}]	[kWh_{th}]	[kW_{th}]	[kW_{th}]	[W/m^2]	[W/m^2]	[W/m^2]	[W/m^2]
Masonry < 1940	2373	8057	11.45	25.65	57	127	71	158
RC 1955-1970	1980	8655	13.89	26.73	69	132	86	165
RC 373/76	1005	8469	9.53	26.29	47	130	59	162
RC EPBD 2010	65	8483	2.79	24.98	14	123	17	154
RC EPBD 2023	1	8426	0.58	24.53	3	121	4	152
Mild Climate								
Masonry < 1940	10684	3608	23.94	24.78	118	122	148	153
RC 1955-1970	9223	4227	24.01	27.20	119	134	148	168
RC 373/76	4971	4542	15.99	26.69	79	132	99	165
RC EPBD 2010	932	4723	8.92	23.53	44	116	55	145
RC EPBD 2023	301	4971	3.93	23.84	19	118	24	147
Cold Climate								
Masonry < 1940	35559	6	41.15	0.46	203	2	254	3
RC 1955-1970	32069	35	39.56	1.30	196	6	244	8
RC 373/76	18878	113	26.52	4.20	131	21	164	26
RC EPBD 2010	6244	1081	12.66	9.55	63	47	78	59
RC EPBD 2023	4668	1142	10.85	9.19	54	45	67	57

Table 5. Results of the analysis for apartment block.

APARTMENT BLOCK								
	TED_h	TED_c	$\dot{Q}_h$	$\dot{Q}_c$	$\dot{q}_h$	$\dot{q}_c$	$\dot{q}_{h,sizing}$	$\dot{q}_{c,sizing}$
Warm Climate	[kWh_{th}]	[kWh_{th}]	[kW_{th}]	[kW_{th}]	[W/m^2]	[W/m^2]	[W/m^2]	[W/m^2]
Masonry < 1940	30724	90204	177.04	370.98	62	130	78	163
RC 1955-1970	26326	105835	193.98	404.27	68	142	85	178
RC 373/76	13285	100910	129.42	388.56	46	137	57	171
RC EPBD 2010	1072	99563	43.31	368.25	15	129	19	162
RC EPBD 2023	75	100174	10.26	365.73	4	129	5	161
Mild Climate								
Masonry < 1940	113761	40361	346.42	326.27	122	115	152	143
RC 1955-1970	105001	50887	373.60	380.25	131	134	164	167
RC 373/76	56229	52951	252.80	361.08	89	127	111	159
RC EPBD 2010	10670	55502	115.30	328.40	41	115	51	144
RC EPBD 2023	4398	59535	81.20	338.59	29	119	36	149
Cold Climate								
Masonry < 1940	367406	9	551.91	2.15	194	1	243	1
RC 1955-1970	351390	423	578.02	24.28	203	9	254	11
RC 373/76	214706	1539	396.42	58.68	139	21	174	26
RC EPBD 2010	71998	11308	193.82	126.96	68	45	85	56
RC EPBD 2023	57332	11713	171.33	124.55	60	44	75	55

Table 6. Saving on peak power sizing ($\dot{q}_{c,sizing}$) in cooling operation.

	SINGLE FAMILY HOUSE	APPARTMENT BLOCK
Masonry < 1940	-10.8%	-17.9%
RC 1955-1970	-15.6%	-20.6%
RC 373/76	-17.1%	-21.9%
RC EPBD 2010	-19.7%	-22.6%
RC EPBD 2023	-20.4%	-24.2%

As it can be clearly highlighted in **Table 4** and **Table 5** at least concerning the energy policies enacted until now, a primary importance in the previous years has been given to measures to improve efficiency concerning the winter energy requirements. Really, starting from the EPBD Recast 2010, with some mentions in EPBD 2002, the control of summer thermal loads and demands have been considered, at least as an aspect to be taken into account in the design phase. For instance, Italian legislation has placed constraints on the summer equivalent solar area, minimum values of thermal mass, and maximum values of peri-odic thermal transmittance, as well as it has been mentioned, more or less explicitly, attention to pay to solutions aimed at the control of thermal gains, such as green roofs (DPR 59/2009) or conventional and innovative technologies for the sensible and latent thermal storing in building components.

In any case, once again, it is highlighted the need to address the issue organically, mainly in the Mediterranean climate (both coastlines and backcountry), where, in addition to quite high cooling peak loads, the criticality of the length of the cooling season emerges, which implies a prolonged impact on energy consumption for space cooling, related emissions, overheating of the urban environment due to the release of condensation heat, in cities often already stressed by the increase in intensity and frequency of heat waves and heat islands connected to anthropogenic activities.

Finally, once thermal demands and the peak loads for space heating and cooling have been analyzed in function of the different architectural technologies and according to different climatic conditions, it has emerged as a criticality in the cooling season. Therefore, the cooling power requirements have been selected as the basis for the study proposed in the next sub-sections, in which the cooling sizing values are matched with the common sizes of residential spaces (living and dining rooms, kitchens, bedrooms, and so on).

3 Air-to-air HP: models, optimal sizing, energy performance

3.1 Identification of heat pump capacities compatible with the simulated buildings

Limiting the analysis to buildings which are using the heat-pumps for the cooling needs only, the scope of this section is to identify the size of a group of heat pumps able to balance the cooling needs, stand-alone or coupled with other heat pumps of the group. Several room dimensions, according to the most common split in buildings, have been considered, assuming four different peak conditions equal to: 140 W/m^2 (max), 130 W/m^2 (medium), 120 W/m^2 (min) and 100 W/m^2 (in case of shading). The values of the peak of previous calculations for the thermal loads of buildings fall within the proposed range. The corresponding cooling load is reported in Table 7(a). For each room, several heat pump capacities commonly used in the market and able to satisfy the requested cooling load have been identified, as shown in Table 7(b). Particularly, six different conditions have been simulated: room surfaces ranging from 10 to 38 m^2 and HP cooling capacities of 1500, 2500, 3750 and 5000 W (approximately equal to 5000, 9000, 12000 and 18000 BTU/h).

Table 7.(a) Requested cooling load for different room surfaces and heat fluxes. (b) Selected rooms and heat pump capacities to simulate.

(a) Requested cooling load [W]	**Heat fluxes in cooling mode [W/m²] in mild and hot Italian Climate conditions. T_{ba} = 30°C, ϕ = 70%**			
	Shading	*Min*	*Medium*	*Max*
Room Surface [m²]	*100*	*120*	*130*	*140*
10	**1000**	**1200**	**1300**	**1400**
16	**1600**	**1920**	**2080**	**2240**
22	**2200**	**2640**	**2860**	**3080**
28	**2800**	**3360**	**3640**	**3920**
38	**3800**	**4560**	**4940**	**5320**

(b) Selected rooms and heat pump capacities to simulate		
Simulated Case	**Room Surface [m²]**	**HP Cooling Capacity [W]**
1	**10**	**1500**
2	**16**	**2500**
3	**22**	**3750**
4	**28**	**3750**
5	**28**	**5000**
6	**38**	**5000**

3.2 Model for the heat pump

The HP machine modelled is a domestic air-source split system, composed of a compressor, two fin-and-tube heat exchangers used as condenser and evaporator, a liquid receiver and a thermostatic expansion valve, able to control a fixed value for the evaporator superheating. The machine has been considered operating in cooling mode, and a schematic is reported in Fig. 3.

All the components for the system investigated among the compressor, the valve and the heat exchangers have been modelled with a common methodology used in the literature and in some previous works of our research group [18], [19]. The global model has therefore been implemented in MATLAB [20]. For the optimization process, several combinations of design parameters have been investigated, such as the rated cooling capacity among the ones identified in section 3.1, the refrigerant fluid among R32, R454C and propane, the evaporator and condenser pinch points and air temperature differences, and other geometrical parameters of heat exchangers. All these combinations, together with other boundary conditions adopted, are reported in Table 8.

For each fluid, a total of approximately 25000 combinations has been simulated. For each solution, both the energy efficiency ratio (EER) and the investment costs (IC) have been evaluated as follows:

$$EER = \frac{\dot{Q}_{ev}}{\dot{W}_{comp} + \dot{W}_{fan,ev} + \dot{W}_{fan,co}} \quad (1)$$

$$IC = IC_{comp} + IC_{valve} + IC_{ev} + IC_{co} \quad (2)$$

$\dot{Q}_{ev}$ is the rated cooling capacity of the simulated HP, whereas $\dot{W}_{comp}$, $\dot{W}_{fan,ev}$, $\dot{W}_{fan,co}$ are respectively the electric power of the compressor, the evaporator and the condenser fans. The investment costs of compressor (IC_{comp}), valve (IC_{valve}), evaporator (IC_{ev}) and condenser (IC_{co}) have been evaluated as a function respectively of the refrigerant mass flow rate and of the heat transfer surfaces, by means of several cost functions reported in Pelella et al., 2023. The optimization process has been carried out by means of a brute-research force.

3.3 Optimal solutions for old, new and transitional fluids in terms of costs and performance, considering the EN-378 limitations

Among all the possible solutions, several have been excluded due to some flammability constraints for each refrigerant. Particularly, the EN-378 regulation [11] establishes the maximum refrigerant charge employable in HPs depending on the room surface dimensions and of the mounting type of systems, evaluated by means of the following relation:

$$m_{max} = 2.5 \cdot LFL^{5/4} \cdot h_0 \cdot A^{1/2} \qquad (3)$$

where LFL is the Lower Flammability Limit, A is the room surface, and h_0 is a coefficient depending on how the system is mounted. For instance, Fig. 4 shows the refrigerant charge limits for the three refrigerants investigated, in case of wall mounted systems.

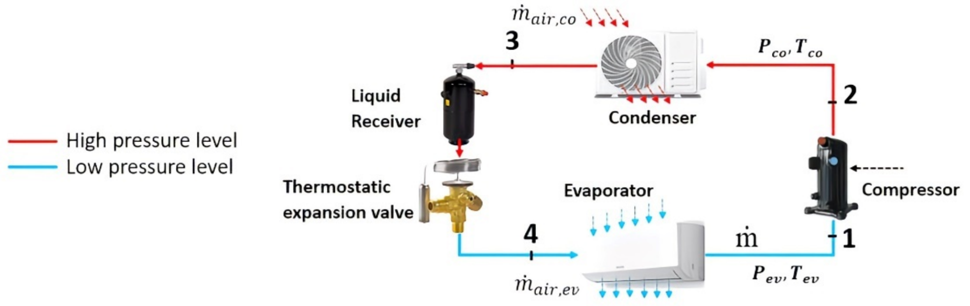

Fig. 3. Schematic of the investigated domestic heat pump split system.

Table 8. Air Source Heat Pump Nominal Parameters and boundary conditions investigated.

Cooling Capacity [kW]		[1.50; 2.50; 3.75; 5.00]
*Indoor dry-bulb and wet-bulb Temperatures [°C]**		27; 19
*Outdoor dry-bulb and wet-bulb Temperatures [°C]**		35; 24
Evaporator Superheating [°C]		5
Compressor Type		Scroll best Technology
Fan Efficiency		65%
Refrigerant Fluid		R32, R454C, Propane
Heat Exchangers	**Internal Unit (Evaporator)**	**External Unit (Condenser)**
Length [m]	0.75	[0.60; 0.65; 0.70; 0.75]**
Height [m]	0.18	[0.60; 0.65; 0.70; 0.75]**
Max Width [m]	0.18	0.08
Tube external diameter [mm]	[6; 7; 8]	
Longitudinal and Transverse Tube Pitches [mm]	3xTube external diameter	
Fin Pitch [mm]	[1.8; 2.5]	[1.0; 2.5]
Tube Thickness [mm]	0.40	
Fin Thickness [mm]	0.115	
Pinch Point [°C]	[2; 3; 4; 6; 9; 11]	[3; 5; 7; 9; 11]
Air Temperature Variation [°C]	[10; 12; 15]	[5; 10]
Tube/Fin Materials	Copper/Aluminum	
** Conditions defined according to the regulation UNI EN 14511* *** Each value corresponding to a rated cooling capacity among the analyzed values*		

It is worth noting that limitations are much more sever for propane (Ashrae Class A3) in which the allowed refrigerant charge is always lower than 1.5 kg due to a higher LFL, whereas R32 and R454C (Ashrae Classes A2L) are characterized by similar values of the maximum allowable refrigerant charges, which are much higher (between approximately 2 and 13 kg depending on the room surface) compared with the ones obtained for propane.
The selection of allowable solutions according to EN-378 is presented in Fig. 5 for propane, for the 6 different room conditions defined in section 3.1.
Firstly, a cooling capacity of the heat pump is chosen (Fig. 5(a)) according to what obtained in **Table 8**. By means of Equation 3, the maximum refrigerant charge is evaluated as a function of the room surface (Fig. 5(c)) and then the corresponding solutions for each simulated HP capacity are filtered (Fig. 5(d)), by excluding all the points not respecting the threshold limits for the refrigerant charge (excluded points are colored in grey). Finally, all the result domains for each room condition simulated are shown in Fig. 5(b) in terms of Investment Costs vs. EER, by distinguishing the solutions respecting (colored lines) and not (grey lines) the EN-378 limitations.

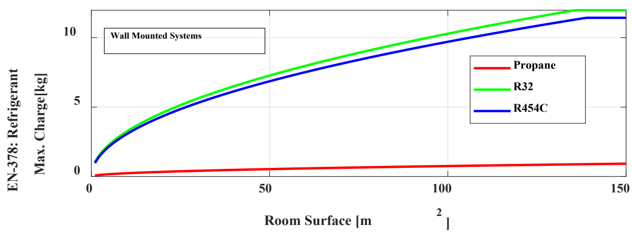

Fig. 4. Maximum allowable refrigerant charge depending on the room surface, according to EN-378.

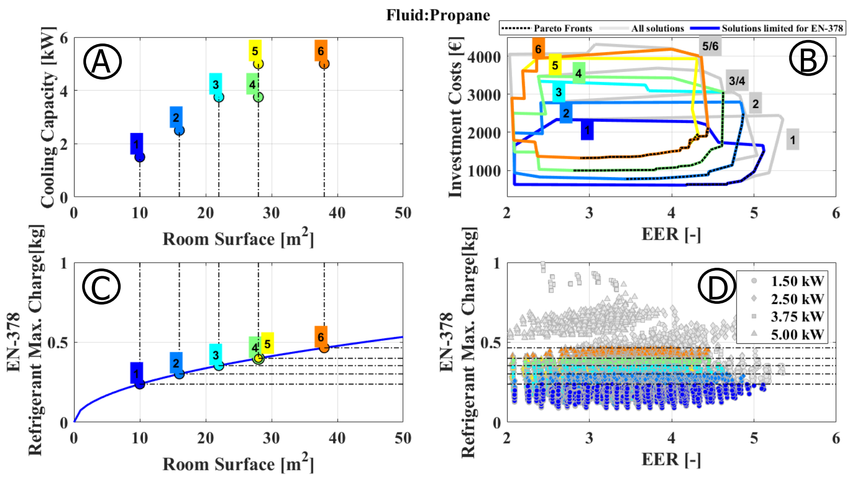

Fig. 5. (a) HP cooling capacity vs. Room Surface. (b) Max refrigerant charge according to EN-378 vs. Room Surface. (c) Exclusion of solutions which does not respect refrigerant charge thresholds. (d) Solution domains, all and limited by EN-378.

Overall, the refrigerant charge limitations for propane tends to exclude all the solutions with the highest EER for each cooling capacity. Moreover, from the Pareto fronts (represented with dashed lines) it is worth noting that, for simulations 3 and 4 (green and light blue lines) the optimal solutions are not influenced by the room surface, whereas for simulations 5 and 6, some optimal solutions remain excluded in case of a lower room surface (with the Pareto front that slightly changes). On the other hand, the EN-378 does not affect the results for the other two A2L refrigerants investigated.

Finally, optimal solutions in terms of investment costs vs. EER, for all the refrigerants and cooling capacities investigated, are presented in Fig. 6. An average market data for R32 systems is also provided, with costs and performance according to the Official Price List of the Veneto Region (2015-2018) [21] and manufacturer catalogues. Moreover, for propane, solutions excluded by the room surface limitations of EN-378 are also highlighted. It is worth noting that, for all the cooling capacities investigated, the optimal solutions for R32 (red lines) are characterized by the highest performance with the lowest costs, the ones for R454C (green lines) by the highest costs and the lowest performance, whereas intermediate values are obtained for propane (blue lines), in which the only solutions that are better than R32 in terms of EER and/or investment costs do not respect the limitations on the maximum refrigerant charge (grey and black lines).

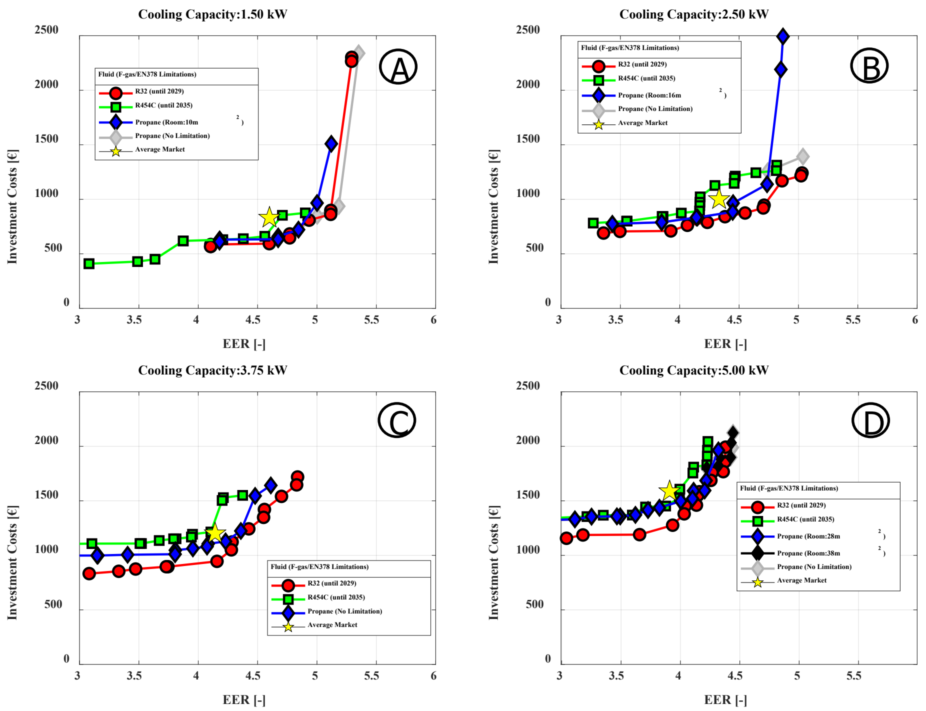

Fig. 6. Optimal solutions in terms of Investment Costs vs. EER for the three fluids investigated, and for cooling capacities of 1.50 kW(a), 2.50 kW(b), 3.75 kW(c) and 5.00 kW(d).

It is important to highlight that, according to results in Fig. 6, it would be possible to produce propane heat pumps with energy performance vs costs very close to the optimal ones for R32 and to the actual market.

4 Conclusions and further development

In this study, the effects of EPBD2023 and F-gas 2024 regulations on domestic air-conditioning systems design are analyzed. Two different investigations have been carried out, one analyzing buildings and the other directly focused on the machines. Particularly, a domestic air-to-air split system operating in cooling mode has been considered. Main outcomes are here provided:

- for both types of buildings and in both climates, increasing savings in the TED for space heating are achieved with the energy efficiency of the building envelope;

- a greater criticality emerges during the summer, especially concerning new and/or refurbished buildings; this highlights the need of special mitigation strategies and technologies to face the overheating in the warm season, even by considering local and global warming, heat islands and future climatic projections;
- even respecting the limitations of the new EPBD the peak load in the cooling does not change in both climates and building types.
- one chosen three refrigerants (R32, actually most used and allowed up to 2029 for cooling capacity less than 12 kW; R454C one of the best candidates for transition period up to 2035) among the investigated optimal solutions in terms of EER vs costs, the EN 378 limits on refrigerant charge affect only propane for size of: 1.5 kW (room of max 10 m^2) and 2.5 kW (room of max 16 m^2). Anyway, the part of the optimal solutions excluded by the limitations of EN 378 are for high cost/high performance; while the ones close to the actual market in terms of cost vs performance are allowed;
- Comparing optimal solutions of the three fluids in terms of EER vs costs, it is possible to see that they are quite close each other: R32 has the best performance fluid in terms of lower investment costs and performances, R454C is the worse, whereas propane is characterized by intermediate solutions;

It is worth noting that this work is a preliminary study, since it does not consider other possible options for cooling needs (e.g. canalized direct expansion systems with capacities higher than 12 kW, or indirect expansion systems). This paper has considered heat pumps for the cooling mode only. Further studies will consider heat pumps for heating and cooling.

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