



# Empirical power-law relationships for the Life Cycle Assessment of heat pump units

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## ABSTRACT

The application of life cycle thinking and the life cycle assessment method is becoming increasingly important in Europe, with the decarbonization targets set by the European Commission. Electric heat pumps (vapor compression) are considered one of the most promising solutions for reducing a building's greenhouse gas emissions. Applying the life cycle assessment method could be challenging when only limited information are available. Reliable tools, for instance, power-law relationships, could be useful for the purpose. Power-law relationships were derived in this article to evaluate the environmental profile of electric heat pumps. 17 745 machines were cataloged according to data from the Italian database "Conto Termico". 10 empirical relationships were created to correlate the mass of the appliance and the refrigerant content for different heat pump technologies (i.e., air-air, air-water, brine-water, and water-water) and refrigerant gases (i.e., R410a, R134a, and R32). The power-law relationships are proven by considering 16 environmental impact categories, based on Environmental Footprint 3.1 EN 15804 method, using deterministic and stochastic approaches. The validation process shows that correlations related to heat pump manufacturing are reliable for all impact categories, while power-refrigerant gas correlations must be used more carefully as they are affected by a more significant error.

## 1. Introduction

The European target to reach complete decarbonization by 2050 highlights the building sector as the core of this transition. As a fundamental element, the sector account for 35–40% of total primary energy consumption and Greenhouse Gas (GHG) emissions (Llantoy et al., 2020).

To reach the scope of reducing energy needs, increasing the share of renewables, and improving environmental efficiency, an effective plan for the sector is necessary (Anastaselos et al., 2016). In this context, electric Heat Pumps (HPs) can be considered one of the most promising solutions in compliance with the European Union's (EU) strategic long-term vision, which indicates the electrification of heat among the main energy transition pathways. The benefits can be summarized in clean energy carriers, highly developed transmission infrastructure compared with liquid fuels, and affordable technology, i.e., heat pumps (Kavvadias et al., 2019). Applying HPs based on the vapor compression cycle under certain boundary conditions (i.e., low water supply temperature – below 55 °C and underfloor heating system for distribution) has several advantages compared to traditional technologies such as

natural gas boilers. The environmental profile of a heat pump over the entire life cycle is significantly lower than a boiler applied under the same conditions (Famiglietti et al., 2023).

The process-based Life-Cycle Assessment - LCA (ISO, 2006a; 2006b) method, among the methodologies that adopt the life cycle approach (such as Material Flow Analysis, Environmental Extended Input Output Table, etc.), is considered the leader in Europe for environmental metrics because it is potentially powerful for strategic and decision-making management (Sala et al., 2017). Several frameworks and programs launched by the European Commission in the present and previous decade adopted the LCA as an environmental metric method (i.e., Level (s) Framework, Environmental Footprint Program, EU Taxonomy, etc.). For this reason, the LCA method is widely applied to assess the environmental profile of products (goods and services) and support several research projects or studies for policy development programs inherent to the buildings (Albertí et al., 2019; Roux et al., 2016). Although the method is widely accepted, the complexities of the assessment, massive data collecting, and data processing are potential obstacles to reaching an acceptable and reliable result (Hauschild et al., 2018). One of the potential causes is the limited access to the primary data (company specific) of complex industrial products, which is a significant challenge

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**Nomenclature**

Q <sub>1</sub>	25th percentile
Q <sub>3</sub>	75th percentile
R <sup>2</sup>	Coefficient of determination
m	Mass/charge of the refrigerant

**Subscripts**

d	declared
el	electric
f	forecasted
nren	non-renewable
th	thermal

**Abbreviations**

A	Acidification
AA	Air-Air heat pump
AW	Air-Water heat pump
BIPV	Building Integrated Photovoltaic panels
BW	Brine-Water heat pump
CAD	Computer Aided Drafting
CC	Climate Change
EF	Eutrophication Freshwater
EFW	Ecotoxicity Freshwater
EH	Equivalent Hours
EM	Eutrophication Marine
EPBD	Energy Performance of Buildings Directive
ET	Eutrophication Terrestrial
EU	European Union
ER-nren	Energy Resources: non-renewable
fU	functional Unit
GHG	Greenhouse Gases

GWP	Global Warming Potential
HHV	Higher Heating Value
HP	electric Heat Pump
HTC	Human Toxicity, Carcinogenic
HTNC	Human Toxicity, Non-Carcinogenic
IC	Impact Category
IQR	Interquartile Range
IR	Ionizing Radiation
JRC	Joint Research Center
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCSA	Life Cycle Sustainability Analysis
LHV	Lower Heating Value
LPG	Liquified Petroleum Gas
LU	Land Use
MRM	Material Resources: Metals/minerals
OD	Ozone Depletion
OLS	Ordinary Least Squares
P	nominal thermal Power
PDF	Probability Density Function
PM	Particulate Matter formation
POF	Photochemical Ozone Formation
SC	Space Cooling
SCOP	Seasonal Coefficient of Performance
SEER	Seasonal Energy Efficiency Ratio
SGUE	Seasonal Gas Utilization Efficiencies
SH	Space Heating
WU	Water Use
WW	Water-Water heat pump

in LCA. Working with incomplete data could lead to unreliable life cycle assessment evaluation with invalid results caused by misleading assumptions. Heat pump units are an example of industrial products in which evaluating their environmental profile requires several data on their components. In this context, various software have been developed in recent years to help practitioners to implement the assessment, i.e., SimaPro® (PRé Sustainability, 2023), GaBi® (Sphera, 2023), OpenLCA® (GreenDelta, 2023), One Click LCA® (One Click LCA Ltd, 2023), and others listed by Hollberg and Ruth (2016). Hollberg and Ruth (2016) classified the software as: (i) “generic”, if the software can be used for any product type, (ii) “Computer Aided Drafting” (CAD) – integrated LCA tools, (iii) “component catalogs tools” (online catalogs for building components), and (iv) “spreadsheet-based tools”. Using software (ii), (iii), and (iv) reduce calculation time compared with (i). In this regard, the absence of primary data for heat and cool generators requires scaling factors, which permit obtaining a new life inventory data set using a few information (Caduff et al., 2014). It becomes essential to have algorithms able to forecast a reliable value of mass related to the nominal power required. So that the implementation in the early stages of design or when the number of machines to be evaluated turns out to be large, e.g., for city-level software as described by Famiglietti et al. (2022).

### 1.1. Previous work on the topic

Previous works have created algorithms to scale up appliances and charge refrigerant gas for HPs starting from the nominal capacity. In particular, Caduff et al. (2011, 2012, and 2014) make empirical relationships for: (i) gasoline engines; (ii) diesel engines, (iii) marine engines, (iv) diesel generators, (v) steam boilers, (vi) biomass furnaces,

(vii) wind turbines, and (viii) electric Heat Pumps. For HPs, they developed 3 algorithms according to the cold source (air-water, brine-water, and water-water) and collecting data on 265 HPs ranging from 3 to 162 kW<sub>th</sub>. The empirical relationships were tested using the ecoinvent library (Frischknecht et al., 2005) for impact category indicators Climate Change (CC) and Ozone Depletion (OD) – 100 years time horizons of the ReCiPe characterization method (Goedkoop et al., 2013). Kemna et al. (2019) have reported empirical relationships for: (i) natural gas boilers, (ii) fuel oil boilers, (iii) electric Heat Pumps, and (iv) refrigerant charge of the HPs. As Caduff et al., the HPs were classified according to cold source, providing one algorithm for air-source electric Heat Pumps and one aggregate for water or brine-source HP. The heating capacity of the empirical relationships ranges approximately from 3 to 100 kW<sub>th</sub>. The algorithm provided for the refrigerant gas change was implemented by taking as a reference the R410a with a machine capacity from 3 to 1000 kW<sub>th</sub>. In this case, the authors described neither the number of machines used to implement the relationships nor a test on the environmental profile results. Famiglietti et al. (2022) elaborate empirical relationships: (i) 1 for natural gas boilers, (ii) 1 for gas absorption heat pumps; (iii) 1 for gas engine heat pumps; (iv) 2 for Electric Heat Pumps (aggregating all together air, brine, and water-source); and (v) 1 for the refrigerant charge of the HPs. The heating capacity of the empirical relationships for HPs ranges from approx. 3 to 40 kW (17 666 data from manufacturers) and from 41 to 1000 kW<sub>th</sub> (78 data from manufacturers), respectively. The algorithm provided for the refrigerant gas change was implemented with a machine capacity from 3 to 1000 kW<sub>th</sub>. The equation was assessed using 16 907 primary data from manufacturers (GSE, 2021) as a mix of appliances that uses R134a (n. 22), R410a (n. 10 235), R22 (n. 53), R32 (n. 6517), R290 (n.8), R404a (n. 1), and R407c (n. 74). The authors did not

test the environmental profile results, as [Kemna et al. \(2019\)](#) they checked the reliability of the algorithms just using the coefficient of determination –  $R^2$  ([Wright, 1921](#)). The  $R^2$  (a number between 0 and 1) describes how well a statistical model predicts an outcome.

## 1.2. Focus and aims of the research

In this work, empirical relationships were created for 4 technologies of electric heat pumps, from now also referred to as “heat pumps” classified as (i) air-air, (ii) air-water, (iii) brine-water, and (iv) water-water, considering the cold source and the carrier used for the distribution of the heat within the building. The authors also implemented algorithms for 3 types the refrigerant gas (i.e., R410a, R134a, and R32) used by the machines, providing the amount of charge in the function of the nominal capacity. The selected refrigerant gases are the main ones used by the installed HPs in Italy ([Moricci et al., 2018](#)). The analysis was performed by collecting (17 745 of HPs and 16 248 charges of refrigerant gas) data published in Conto Termico database ([GSE, 2021](#)), which offers a list of technologies by providing the name of the manufacturer, the model, the nominal power, the coefficient of performance, and the type of refrigerant gas used. Data from Conto Termico were integrated with data deducted from technical datasheets provided by the manufacturers on their websites (i.e., total mass of the appliance and charge of the refrigerant gas), with 3 different aims:

- providing consistent and reliable empirical correlations for LCA application, extending the technology (heat pumps and refrigerant gas) evaluated by the previous authors;
- performing a comparison between the environmental profile of heat pumps evaluated utilizing primary data and secondary data calculated by the empirical correlations;
- providing uncertainty analysis (error propagation with the null hypothesis test).

The novelty of this research consists in: (i) creating specific empirical correlations for refrigerant gas R32 never investigated before; (ii) creating different empirical correlations for four typologies of heat pumps (air-air, air-water, brine-water, and water-water) evaluated aggregated by [Famiglietti et al. \(2022\)](#) for the Italian market; (iii) testing new correlations of a significant sample of data concerning the heat pumps and charges of refrigerant gas compared with Caduff et al. (256 appliances against 17 745 of HPs and 16 248 charge of refrigerant gas); and (vi) apply a holistic validation method beyond the coefficient of determination and the GHG emissions. In the literature, energy systems are commonly assessed concerning Climate Change ([Ciacci and Passarini, 2020](#); [Martín-Gamboa et al., 2017](#)). Considering potential impacts in addition to GHG emissions is of considerable importance to avoid burden-shifting (decreasing GHG emissions and increasing other impact categories), as highlighted by previous authors ([Laurent et al., 2012](#)). Uncertainty analysis via error propagation was as well performed to test the correlations obtained. The uncertainties analysis was executed following the Monte Carlo (MC) simulation method and testing the results by the hypothesis test. Thus, the article’s novelty can also be traced to the uncertainty analysis performed not investigated by the previous authors.

## 2. Material and methods

The following sections present the material and methods to create the empirical correlations (section 2.1) and test their efficiency (section 2.2).

### 2.1. Creation of the empirical correlations (power-law relationships)

This section explains how the empirical correlations were created, describing the data input, technical systems, and correlations between

**Table 1**

Technologies and refrigerant gases studied.

Technology or refrigerant gases	No. of heat pumps evaluated	Capacity range [kW <sub>th</sub> ]
Air/Air (AA)	15 334	From 2 to 35
Air/Water (AW)	1616	From 2 to 34.9
Air/Water (AW)	44	From 35 to 948
Brine/Water (BW)	58	From 3 to 32
Water/Water (WW)	41	From 7 to 35
R32	6021	From 2 to 28
R410a (B/W excluded)	8211	From 2 to 34.9
R410a (B/W excluded)	47	From 35 to 948
R410a (for B/W)	52	From 4 to 30
R134a	17	From 280 to 787

mass and capacity. It is important to note that the term “heat pump” is also used to define chillers. In this specific case, the research is focused on heating systems only.

A database collecting all the Heat Pumps in the Italian market was set up by importing the required information from Conto Termico database, integrating missing information from technical datasheets provided by the manufacturers on their websites (see the supplementary material – Microsoft Excel files “Database”). Conto Termico provided a list of 18 495 HPs, that were collected and described for: (i) power supply typology (electric); (ii) sources adopted for the heat exchange; (iii) thermal capacity; (iv) presence of the inverter; (v) Coefficient of Performance (COP); (vi) mass of the machine provided by the manufacturer; (vii) typology of refrigerant gas operating inside the machine; and (viii) mass of the gas refrigerant. The analysis excluded HPs in which it was not possible to collect the necessary information in the preliminary phase. For power-mass analysis, all the HPs with a storage tank installed (equal to 750) were excluded not to influence the work’s aim as the mass increases significantly (approx. 300 kg) with the same nominal capacity. Thus, the analysis considered data for 17 745 HPs. Similarly, regarding the power-charge correlations of the refrigerant, 2247 items were excluded from the list provided by Conto Termico because the installed refrigerant gas could not be traced with certainty; therefore, the analysis reflected data for 16 248 refrigerant gas charges. The key properties were reported under the following standard conditions:

- Brine with 0 °C and Water with 35 °C;
- Air with 2 °C and Water with 35 °C;
- Water with 10 °C and Water with 35 °C;
- External Air 7 °C and internal Ambient temperature at 20 °C.

Information gathered from manufacturers’ datasheets enabled the authors to subdivide heat pumps according to the cold source used for heat exchange and the type of refrigerant gas used.

Appliances were grouped into: (i) cold source adopted to work and (ii) refrigerant gas installed (regardless of the type of machine, as the thermodynamic cycle is the same - vapor compression cycle). The correlations studied and their range of applications are reported in [Table 1](#).

The Ordinary Least Squares (OLS) regression method was utilized to describe the power-mass relationships of each technology analyzed. The functions chosen for representing the behavior among the properties were equation (1) linear function and equation (2) polynomial 2<sup>nd</sup> order function:

$$m_i = b_j \bullet P_i + c_j \quad (1)$$

$$m_i = a_j \bullet P_i^2 + b_j \bullet P_i + c_j \quad (2)$$

Where: ( $m_i$ ) is the mass of the appliance (i) [kg]; ( $P_i$ ) is the nominal capacity on the water [kW<sub>th</sub>] of the appliance (i); ( $a_j$  and  $b_j$ ) are leading terms for the heat pump technology (j); and ( $c_j$ ) is the constant term the heat pump technology (j).

The correlations’ reliability was analyzed by assessing the coefficient

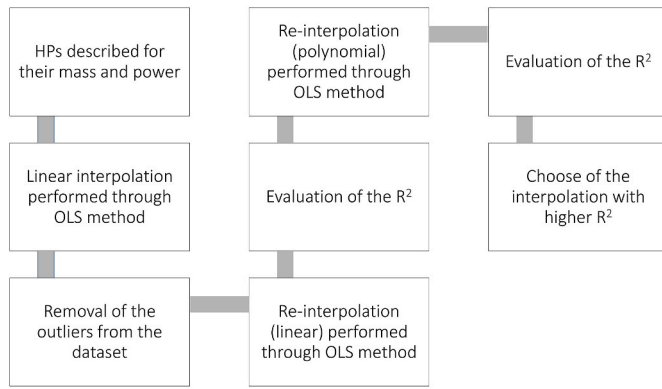


Fig. 1. Graphical distribution of the steps involved in the procedure.

of determination –  $R^2$  (Wright, 1921). The potential correlations were described using the above functions, selecting the higher  $R^2$  obtained for each technology, excluding outliers. The procedure was applied as follows:

- for each component in the dataset, the mass was recalculated using the assumed correlation as a function of capacity (known);
- a percentage difference was calculated between the forecasted mass from the correlation and that declared in the datasheets for each appliance as follows:

$$\text{Difference} [\%] = \frac{m_f - m_d}{m_d} \quad (3)$$

Where:  $m_f$  is the forecasted mass and  $m_d$  is the declared mass;

- the outliers were determined by the difference using the box plot method, following equation (4) (Tukey, 1972):

$$Q_1 - 1.5 \cdot IQR \leq \text{Difference} \leq Q_3 + 1.5 \cdot IQR \quad (4)$$

Where:  $Q_1$  and  $Q_3$  are the 25th and 75th percentile, and  $IQR$  is the InterQuartile Range (IQR).

The outlier exclusion procedure was necessary to increase the correlations reliability. Such as initially, the dataset of Water/Water consisted of 58 appliances (with  $R^2$  equal to 0.46). Removing 17 outliers has allowed the generation of a more reliable correlation ( $R^2$  equal to 0.57). Fig. 1 represents graphically the steps involved in the procedure described before.

## 2.2. Life-Cycle Assessment execution

This section describes the methodology adopted to test the empirical correlations according to the LCA method. It introduced and explained all the aspects related to system boundaries, multifunctionalities, cut-off rules, functional unit, life cycle impacts assessment, uncertainty analysis via error propagation, and bottom-up process-based life cycle inventory analysis, considering the attributional approach (micro-level decision support) for planning and pre-design propose (European Commission et al., 2010; UNEP, 2011). The outcomes were obtained by modeling an engine tool using *Brightway 2.0* (Mutel, 2017), using the ecoinvent 3.9.1 EN 15804 library (Wernet et al., 2016), and the Environmental Footprint 3.1 EN 15804 as a characterization method (Fazio et al., 2018). The entire procedure is described in the sections below.

### 2.2.1. Product systems

The energy systems are evaluated with a cradle-to-grave approach, considering the following life cycle phases:

- component productions (raw material supply and production);
- aspects concerned with the manufacturing process (also considering the transport inputs);
- packaging and distribution of the materials (including the transports required to move heat pumps from the manufacturing place to the housing units);
- use stage (energy vector consumptions plus maintenance, leakage of refrigerant gas included);
- end-of-life stage (transport, waste processing for reuse, recovery or/and recycling, and disposal).

Due to a lack of data, the installation phase was not considered. Since it has a low impact compared to other phases, this phase could be

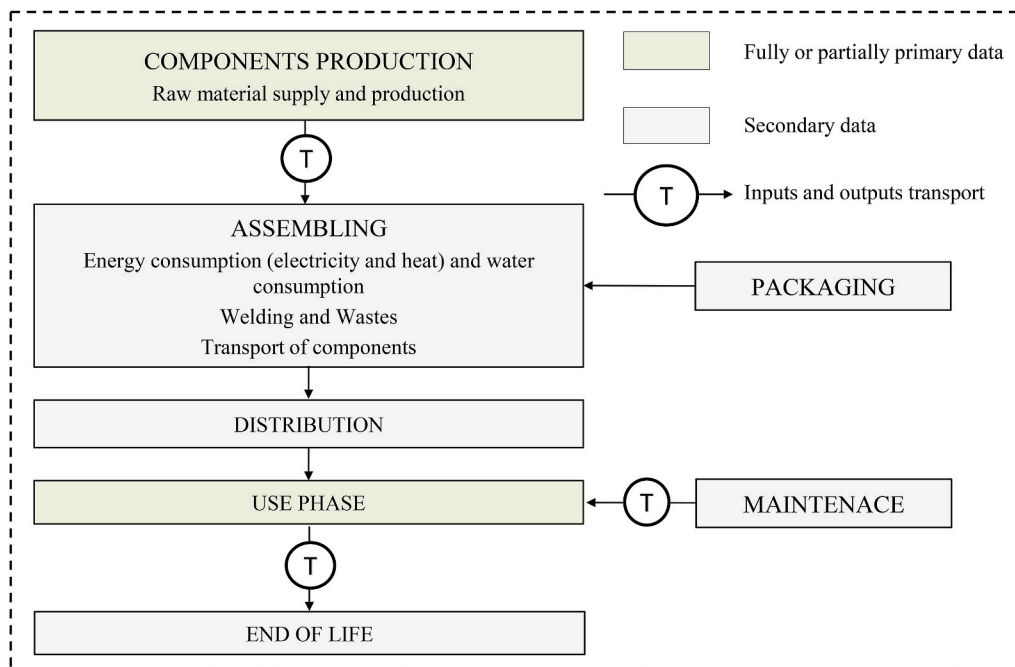


Fig. 2. Life Cycle phases and data considered for modeling the heat pumps.

**Table 2**  
Life Cycle Inventory of the heat pumps analyzed.

Items	Unit	Amount	Source
<i>Components</i>			
Reinforced Steel	kg	$58.46\% \times \text{HP mass}$	Famiglietti et al., (2022)
Steel low-alloyed	kg	$15.59\% \times \text{HP mass}$	
Copper	kg	$17.38\% \times \text{HP mass}$	
Elastomer	kg	$7.79\% \times \text{HP mass}$	
Polyvinylchloride	kg	$0.75\% \times \text{HP mass}$	
Refrigerant gas	kg	Mass of the refrigerant gas	
Air fun	kg	1.90	
Electronic components	kg	1.00	
<i>Manufacturing process</i>			
Water consumption	kg	$5.4 \times \text{HP mass}$	ecoinvent
Emissions of water in air	m <sup>3</sup>	$15\% \times (0.001 \times \text{water consumption})$	
Emissions of water in water	m <sup>3</sup>	$2\% \times (0.001 \times \text{water consumption})$	
Wastewater treatment	m <sup>3</sup>	$83\% \times (0.001 \times \text{water consumption})$	
Lubricating oil	kg	$27\% \times \text{nominal power}$	
Electricity	kWh <sub>e</sub>	$14 \times \text{nominal power}$	
Heat	MJ	$136.5 \times \text{nominal power}$	
Refrigerant gas	kg	$3\% \times \text{mass of the refrigerant}$	
Transport input	kg	Charge of the refrigerant gas	Kemna et al., (2019)
	km	300 (electric train)	
	km	700 (lorry >32 tons)	
<i>Packaging</i>			
Plastic film	kg	$\text{norm.dist}(\text{HP mass}, 300, 150) \times 5$	Kemna et al., (2019)
Polystyrene	kg	$\text{norm.dist}(\text{HP mass}, 300, 150) \times 2.5$	
Corrugated board	kg	$\text{norm.dist}(\text{HP mass}, 300, 150) \times 5$	
<i>Distribution</i>			
Transport to consumer	km	500 (lorry 16–32 tons)	Kemna et al., (2019)
	km	200 (light commercial vehicle)	
	km	50 (light commercial vehicle)	
<i>Use phase</i>			
Electricity	kWh <sub>e</sub>	$2066 \text{ h} \times \text{Nominal power} \times \text{lifespan}$	–
Refrigerant gas	kg	$2\% \times \text{lifespan} \times \text{mass refrigerant}$	PEP ecopassport
<i>Maintenance</i>			
Components substitution	–	$\text{Components} \times 1\% + \text{Manufacturing} \times 1\%$	Kemna et al., (2019)
Transport to consumer	tkm	$25 \text{ km} \times \text{lifespan}$	
<i>End of life</i>			
Copper	kg	97% to recycling	Kemna et al., (2019)
	kg	3% to landfill	
Steel	kg	97% to recycling	
	kg	3% to landfill	
Plastic	kg	70% to recycling	
	kg	30% to landfill	
Electronic components	kg	67% to incineration	
	kg	33% to landfill	
Packaging cardboard	kg	83.20% to recycling	
	kg	5.76% to incineration	
Packaging plastics	kg	10.97% to landfill	
	kg	31.90% to recycling	
Refrigerant gas	kg	23.35% to incineration	
	kg	44.46% to landfill	
Transport to the treatment plant	kg	$50\% \times \text{mass refrigerant gas}$	Famiglietti et al., 2021b
	kg	$80\% \times \text{mass refrigerant gas}$	
	km	50	

considered negligible (Famiglietti et al., 2021; Favi et al., 2018; Oregi et al., 2015).

Fig. 2 is a simplified flow chart of the heat pump. In green, the blocks are reported fully or partially evaluated using primary data (foreground processes, i.e., direct access to information is available), while in grey, the part of the system is modeled according to secondary data (background processes, i.e., no direct access to information is possible – modeled using scenarios). For example, the components production phase (green block in Fig. 2 – partially assessed using primary data) was evaluated considering the total mass of the appliances using the technical sheets and information regarding the share of each component by information collected provided by the manufacturers (primary data). The exchanges with Nature for producing a specific amount of material

used (i.e., 1 kg of steel, copper, etc.) were derived from the ecoinvent library (secondary data).

Two scopes were defined for the analysis to have a complete overview of the appliance components:

- Scope No. 1 (complete assessment), considering the entire life cycle and components;
- Scope No. 2 (partial assessment),
  - excluding all the activities linked with the use phase of the machines (i.e., electricity consumptions) and the refrigerant gas (i.e., charge, leakages, transports, and end-of-life treatments) for the power-appliance mass correlations;



- o evaluating exclusively gas-related activities over the entire life cycle from those inherent in the machine for the power-mass charge of refrigerant gas correlations.

### 2.2.2. Technical system boundaries

The environmental burdens of co-production or end-of-life treatment processes were assessed utilizing the system model “allocation, cut-off, EN 15804” provided by ecoinvent 3.9.1 library. The system model classified the intermediate exchanges into one of 3 categories: allocatable, recyclable, and waste. Allocatable exchanges were assessed following co-product partitioning methods (physical or other relationships) implemented in the library. The cut-off point between the primary and secondary systems for recyclable products complies with the end-of-waste criteria of the standard EN 15804. For modeling the end-of-life scenarios, waste producers bear the burden of waste treatment based on the “polluter pays” principle; consumers of recycled products receive them without charge. The cut-off rule was set at 1% in terms of environmental impact within the system boundaries described above, meaning that inputs and outputs below this threshold were not included in the LCA models. E.g., seals, glues, transport, and transport of packaging materials to the manufacturing sites.

### 2.2.3. Functional unit

The functional unit for the analysis was set as 1 kWh of thermal energy provided following the indication reported by Klöpffer and Grahl (2014), Hauschild et al. (2018), and previous articles on energy systems for buildings (Caduff et al., 2014). The authors considered 2066 equivalent hours (full capacities) per year. The lifespan of the appliances was fixed equal to 21 years, as defined by Kemna et al. (2019).

### 2.2.4. Impact categories analyzed

All the analysis performed on the HPs considered 16 impact categories, following the Environmental Footprint (EF) method 3.1 EN 15804 – characterization method of EF initiative: Climate Change (CC) with a time horizon of 100 years; Ozone Depletion (OD) with a time horizon of 100 years; Ionizing Radiation (IR); Photochemical Ozone Formation (POF); Particulate Matter (PM) formation; Human Toxicity, Non-Carcinogenic (HTNC); Human Toxicity, Carcinogenic (HTC); Acidification (A); Eutrophication Freshwater (EF); Eutrophication Marine (EM); Eutrophication Terrestrial (ET); Ecotoxicity Freshwater (EF); Land Use (LU); Water Use (WU); Energy Resources (ER) non-renewable; Material Resources: Metals/minerals (MRM).

### 2.2.5. Life-cycle inventory analysis

All the HPs were tested considering the heat provided by the appliance during its service life (excluding the distribution system within the building), and evaluated as follows:

$$\text{Heat provided } [kWh_{th}] = P \bullet EH \bullet \text{lifespan} \quad (5)$$

Where:

- P, is the nominal thermal power provided by the manufacturer in the HPs datasheet (in  $kW_{th}$ );
- EH, are the Equivalent Hours equal to the ratio of the energy produced in a year to the nominal thermal power: moreover, the hours of operation at full capacity to generate thermal energy (in hours per year). The authors considered 2066 as the suitable equivalent hours for the analysis. The EH was calculated using the bin method for the average climate as a reference condition (Strasbourg, France) defined by the European ERP Directive (European Parliament, 2009);
- lifespan assumed as 21 years.

The quantitative information needed for modeling the Life-cycle Inventories (LCIs) was gathered from existing literature, as shown in Table 2.

### 2.3. Validation of the empirical correlations

Three nominal power values were selected along with the domain of each power-mass relationship to have a response for low, middle, and high capacities, as shown in Fig. 3. The LCA analyses were performed considering the declared mass ( $m_d$ ) and the forecasted mass ( $m_f$ ). The HPs were selected from those close to the standard deviation values calculated considering the declared masses in the domain of the power-mass relationship (Table 1). As well as deterministic comparison, the results obtained were also evaluated by error propagation using the Monte Carlo (MC) simulation method (stochastic comparison). For each activity data collected, the MC was performed considering the epistemic uncertainty (related to an incomplete state of knowledge) and the stochastic uncertainty related to the inherent variability of the natural world (Clavreul et al., 2012; Pizzol, 2019). For the activity data collected, the geometric standard deviations ( $\sigma_g$ ) used in the MC model were assessed utilizing the pedigree matrix provided by Rolf Frischknecht et al. (2005). The number of executions was fixed equal to 1000 with dependent sampling for each system. To summarize, the number of executions was determined by: (i) 1000 samples for simulation with primary data, or declared data ( $data_d$ ); (ii) 1000 samples for the simulation with forecasted data ( $data_f$ ); (iii) 3 heat pumps or charges of refrigerant gas for each correlation; (iv) 10 empirical correlations; (v) 16 environmental impact category tested. The simulations provided 960 000 outcomes for 480 tests (per scope, see section 2.2.1). The results obtained by the two scenarios (HPs evaluated with primary data and forecast data – empirical relationship) were checked to verify if they were statistically comparable. For each impact category, the probability of the forecasted data being higher than the primary data was assessed according to the column vector shown below:

$$\text{Differences}_{i,j} = \begin{bmatrix} x_{i,j,1} \text{ data}_f - x_{i,j,1} \text{ data}_d \\ \vdots \\ x_{i,j,n} \text{ data}_f - x_{i,j,n} \text{ data}_d \end{bmatrix} \quad (6)$$

Where (i) is the analyzed technology among the 10 studied (see section 2.1), (j) is the machine capacity, and (n) is the number of iterations of the MC analysis. The hypothesis test was performed to increase the consistency of the results achieved with respect to the deterministic approach. It was implemented as follows:

- Shapiro-Wilk test in order to verify if the distributions provided by MC analysis were normally distributed (Shapiro and Wilk, 1965). The numbers closer to 1 are approximal to a normal distribution.
- A further check on the distribution's normality was performed graphically through a quantile distribution analysis. Quantile-Quantile plot graphs (Q-Q plot) were made on the MC analyses that returned lower Shapiro values. Q-Q plots were used to graphically compare the observed variables with the normal distribution. If

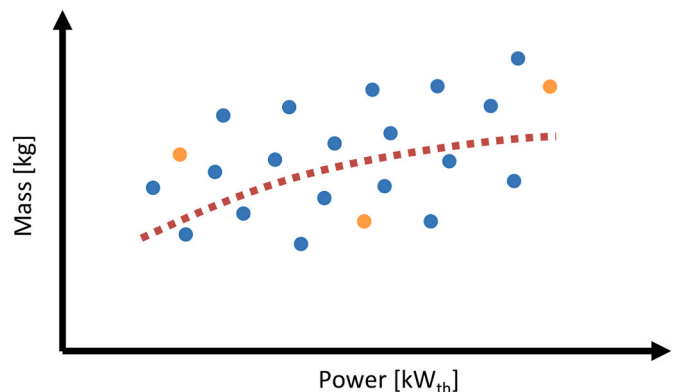


Fig. 3. Position of the selected tests for.

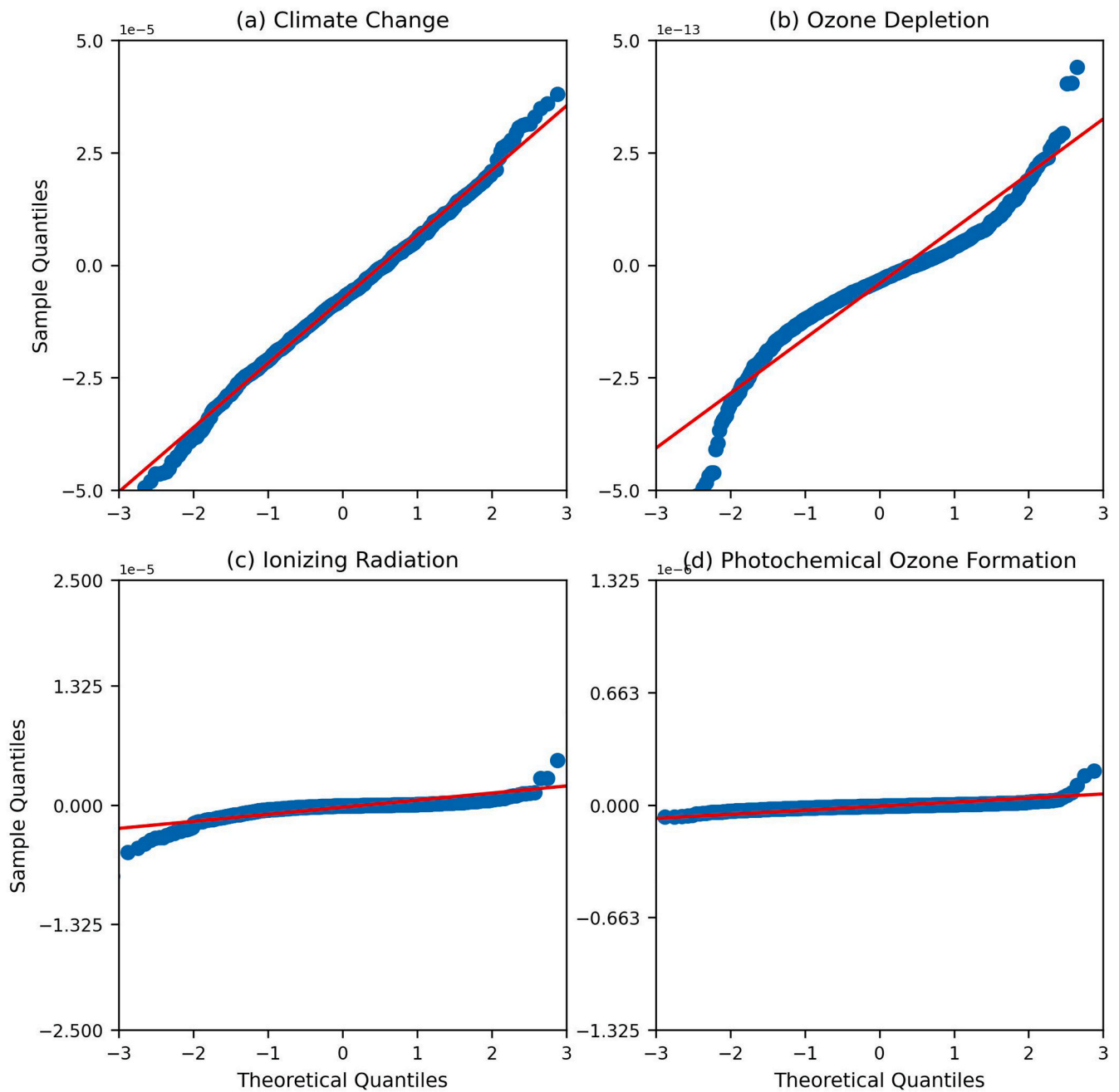


Fig. 4. Examples of Q-Q plots for testing a water-to-water heat pump with a rated capacity of 12.6 kW for: (i) Climate Change, (ii) Ozone Depletion, (iii) Ionizing.

Table 3

Forecasted and declared masses for the validation.

Technology	Low capacity		Medium capacity		High capacity	
	Forecasted mass [kg]	Declared mass [kg]	Forecast mass [kg]	Declared mass [kg]	Forecast mass [kg]	Declared mass [kg]
Air-Air	41.85	47.00	110.73	86.00	220.31	194.00
Air-Water < 35 kW <sub>th</sub>	63.79	59.00	204.11	161.00	443.94	527.00
Air-Water ≥ 35 kW <sub>th</sub>	2320.24	2768.00	5483.11	4060.00	7467.10	7070.00
Brine-Water	130.45	157.00	166.82	139.00	198.94	180.00
Water-Water	99.75	125.00	125.28	150.00	183.30	150.00
R32	0.91	1.03	3.29	3.75	5.05	5.20
R410a < 35 kW <sub>th</sub>	1.34	1.70	4.32	3.60	6.51	7.10
R410a ≥ 35 kW <sub>th</sub>	26.90	39.00	66.20	58.00	124.80	138.00
R410a (for Brine-Water HPs)	1.32	1.05	3.63	2.65	5.59	3.50
R134a	99.00	115.00	173.00	150.00	260.00	260.00

**Table 4**Correlations power-appliance mass with  $R^2$  value.

Technology	Interpolation relationship	$R^2$	Range
Air-Air	$m = 6.2616 \cdot P + 10.5460$	0.86	2 kW–35 kW
Air-Water	$m = 12.7570 \cdot P$	0.85	3 kW–34.9 kW
Air-Water	$m = -0.0038 \cdot P^2 + 11.4250 \cdot P + 51.2774$	0.98	35 kW–948 kW
Brine-Water	$m = -0.1092 \cdot P^2 + 6.6935 \cdot P + 97.4920$	0.51	3 kW–32 kW
Water-Water	$m = 3.8683 \cdot P + 61.4500$	0.57	7 kW–35 kW
R32	$m = -0.0016 \cdot P^2 + 0.2104 \cdot P + 0.4105$	0.66	3 kW–19 kW
R410a	$m = -0.0013 \cdot P^2 + 0.2264 \cdot P + 0.6693$	0.64	2 kW–34.9 kW
R410a	$m = 0.3539 \cdot P - 18.3790$	0.97	35 kW–948 kW
R410a (for Brine-Water HPs)	$m = -0.0014 \cdot P^2 + 0.2195 \cdot P + 0.3173$	0.97	4 kW–30 kW
R134a	$m = 0.3539 \cdot P - 18.3790$	0.97	300 kW–787 kW

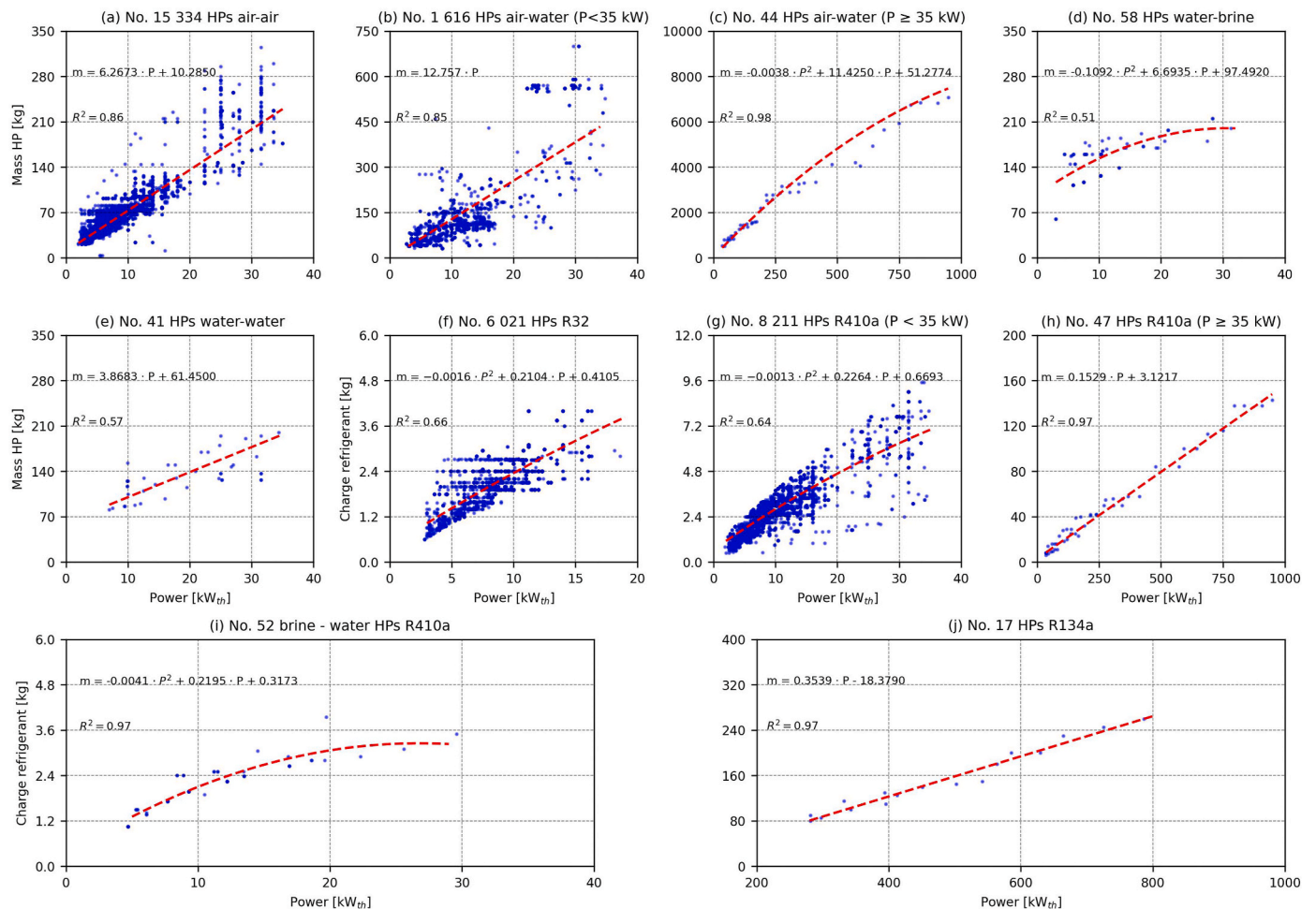
the plots were on the diagonal, running from bottom to top and left to right, the distribution would be normal, as shown in Fig. 4. However, it should be noted that none of the distributions returned results that cast doubt on the normality hypothesis (most of the points in the distribution recline on the line).

A hypothesis test (paired  $t$ -test) was implemented to evaluate the statistical comparability of the paired distributions from forecasted mass values and primary data. It was implemented to predict the probability of having false positive (Type I error) and negative (Type II error) for normally distributed results. The statistical comparability of the samples from the MC analyses was assessed utilizing p-value analysis. The test calculates the distance of the two mean values according to the number of standard deviations, predicting the probability of committing Type I

error (reject the null hypothesis  $H_0$  when  $H_0$  is true) and Type II error (accept  $H_0$  when the alternative hypothesis  $H_1$  is true). The hypothesis were structured as shown in equation (7).

$$\begin{cases} H_0 : \mu_{\text{forecasted}} = \mu_{\text{primary}} \\ H_1 : \mu_{\text{forecasted}} \neq \mu_{\text{primary}} \end{cases} \quad (7)$$

In this article, the authors want to demonstrate that the environmental profiles assessed using the mass-nominal power correlations created are equal to those assessed with primary data; thus, the rebuttal is based on the level of significance of  $\beta$ , for Type II error (equal to 0.15, assessed considered an  $\alpha$  of 0.05). The p-value is then used to reject the alternative hypothesis if it is lower than a predetermined significance level  $\beta$  (when the probability of committing Type I error is higher than 35%).



**Fig. 5.** Empirical equation involved in the study in relation to the samples adopted: (a) air-air HPs, (b and c) air-water HPs, (d) water-brine HPs, (e) water-water HPs, (f).



**Table 5**  
Comparison among empirical correlations.

Technology	Item	This study	Caduff et al., (2014)	Kemna et al., (2019) <sup>(a)</sup>	Famiglietti et al., (2022) <sup>(b)</sup>
Air-Air	No. samples	15 334	Not provided	Approx. 35	17 666
	R <sup>2</sup>	0.86		0.69	0.56/0.95
	Function	Linear		Logarithmic	Exponential/Linear
Air-Water	No. samples	1660	100	Aggregated, see above	Aggregated, see above
	R <sup>2</sup>	0.85/0.98			
	Function	Linear/Polynomial			
Brine-Water	No. samples	58	117	Approx. 20	Aggregated, see above
	R <sup>2</sup>	0.51			
	Function	Linear			
Water-Water	No. samples	41	48	Not provided	Aggregated, see above
	R <sup>2</sup>	0.57			
	Function	Linear			
R32	No. samples	0.66	Not provided	Not provided	16 907
	R <sup>2</sup>				
	Function				
R410a	No. samples	0.64/0.97	Not provided	Approx. 50	Aggregated, see above
	R <sup>2</sup>				
	Function				
R134a	No. samples	0.97	105	Not provided	Aggregated, see above
	R <sup>2</sup>				
	Function				

<sup>a</sup> The charge of refrigerant gas is provided considering the R134a as a reference refrigerant. Based on R134a, three different correlations are provided (i.e., for Air-Water, Brine-Water, and Water Water heat pumps).

<sup>b</sup> Empirical correlations are aggregated: (i) 1 for air, brine, and water source heat pumps and (ii) 1 for the refrigerant gases.

Since the alternative hypothesis tests were studied in pairs, using the Bonferroni correction (Bonferroni, 1936) to the significance level was unnecessary. In the section on stochastic results, the authors also show the probability of committing the Type I error in the dedicated tables to understand the relationship between errors.

Table 3 presents the forecasted and declared masses (appliances and refrigerant gas charges) of the heat pumps selected for validating the empirical correlations. The capacities are the following: (i) 5, 16, and 33.5 kW<sub>th</sub>, for Air/Air; (ii) 5, 16, 34.8, 213.8, 592, and 948 kW<sub>th</sub>, for Air/Water; (iii) 5.4, 13.2, and 27.44 kW<sub>th</sub>, for Brine/Water; (iv) 9.9, 16.5, and 31.5 kW<sub>th</sub>, for Water/Water; (v) 3, 15.5, and 28 kW<sub>th</sub>, for R32; (vi) 3, 18, 31.5, 155.6, 412.6, and 796 kW<sub>th</sub>, for R410a excluding Brine/Water HPs; (vii) 4.7, 16.90, 29.60 kW<sub>th</sub>, for R410a – Brine/Water HPs; and (viii) 332.30, 541.50, and 786.7 kW<sub>th</sub>, for R134a.

### 3. Results and discussion

This section presents the empirical correlations developed and the results obtained for validation by deterministic (without uncertainty analysis) and stochastic approaches (with uncertainty analysis based on error propagation).

#### 3.1. Mass–nominal power correlations

Table 4 reports the correlations between Masses/refrigerant charges (m) and nominal thermal Powers (P). In total, 10 relationships were presented, showing the R<sup>2</sup> values and the range of application. It is important to emphasize that forecasted mass values for all the HPs do not consider the presence of a potential hot water storage tank integrated.

Fig. 5 represents all the appliances and refrigerant gases involved in the study. The analyzed data sample (heat pumps and refrigerant gases) are depicted as a scatter plot, where empirical correlations are shown

graphically as a trend line, also reporting the equations presented in Table 4.

Comparing the results obtained with the correlations shown by previous authors, the following can be summarized in: (i) higher samples of data analyzed and R<sup>2</sup> obtained and (ii) R32 correlation not provided by previous authors. Only Caduff et al. (2014) show two correlations with more extensive data samples and higher R<sup>2</sup> (i.e., brine-water and water-water). The authors, however, indicate that the analyzed nominal power range is different: (i) in this study, from approx. 3 to 35 kW<sub>th</sub>, (ii) Caduff et al. (2014) from 10 to 100 kW<sub>th</sub>. The comparison is summarized in Table 5.

#### 3.2. Deterministic results

The characterization results for the Climate Change impact category are presented in Table 6. The outcomes are quantified according to the functional unit (fU), 1 kWh<sub>th</sub> provided by the heat pumps, considering an operation of 2066 equivalent hours (full capacities) per year with a lifespan of 21 years. The results are presented for (i) forecasted and declared masses, (ii) technologies, and (iii) capacities selected for validation. The outcomes are reported considering the two product systems described in section 2.2.1, scope No. 1 and No. 2. The results obtained for the other impact categories evaluated are presented in the supplementary material (Microsoft Excel file “Characterization results - deterministic”) to avoid redundant data.

The results obtained considering the Climate Change impact category were consistent with what was found in previous studies (in terms of order of magnitude): Famiglietti et al. (2021, 2022, 2023), Naumann et al. (2022), Sevindik et al. (2021), Latorre-Biel et al. (2018), and Greening and Azapagic (2012). The scientific articles report the following range values, from 88 to 276 gCO<sub>2</sub>eq/kWh<sub>th</sub>, considering scope No. 1. The high variability of the results is dependent mainly on four parameters: (i) the Coefficient Of Performance (COP), in the case of

**Table 6**  
Characterization results for climate change impact category (gCO<sub>2</sub>eq/fU).

Technology	Scope (boundaries)	Low capacity		Medium capacity		High capacity	
		Forecasted mass	Declared mass	Forecast mass	Declared mass	Forecast mass	Declared mass
Air-Air	No. 1	$1.34 \bullet 10^{+02}$	$1.34 \bullet 10^{+02}$	$1.27 \bullet 10^{+02}$	$1.27 \bullet 10^{+02}$	$1.25 \bullet 10^{+02}$	$1.25 \bullet 10^{+02}$
	No. 2	$1.82 \bullet 10^{+00}$	$1.84 \bullet 10^{+00}$	$8.45 \bullet 10^{-01}$	$8.38 \bullet 10^{-01}$	$8.44 \bullet 10^{-01}$	$8.41 \bullet 10^{-01}$
Air-Water < 35 kW <sub>th</sub>	No. 1	$1.34 \bullet 10^{+02}$	$1.34 \bullet 10^{+02}$	$1.25 \bullet 10^{+02}$	$1.25 \bullet 10^{+02}$	$1.33 \bullet 10^{+02}$	$1.33 \bullet 10^{+02}$
	No. 2	$1.67 \bullet 10^{+00}$	$1.67 \bullet 10^{+00}$	$1.32 \bullet 10^{+00}$	$1.31 \bullet 10^{+00}$	$7.74 \bullet 10^{+00}$	$8.03 \bullet 10^{+00}$
Air-Water ≥ 35 kW <sub>th</sub>	No. 1	$1.26 \bullet 10^{+02}$	$1.26 \bullet 10^{+02}$	$1.24 \bullet 10^{+02}$	$1.24 \bullet 10^{+02}$	$1.24 \bullet 10^{+02}$	$1.24 \bullet 10^{+02}$
	No. 2	$1.49 \bullet 10^{+00}$	$1.50 \bullet 10^{+00}$	$9.12 \bullet 10^{-01}$	$9.02 \bullet 10^{-01}$	$9.62 \bullet 10^{-01}$	$9.60 \bullet 10^{-01}$
Brine-Water	No. 1	$1.30 \bullet 10^{+02}$	$1.30 \bullet 10^{+02}$	$1.23 \bullet 10^{+02}$	$1.23 \bullet 10^{+02}$	$1.24 \bullet 10^{+02}$	$1.24 \bullet 10^{+02}$
	No. 2	$3.32 \bullet 10^{+00}$	$3.34 \bullet 10^{+00}$	$1.39 \bullet 10^{+00}$	$1.38 \bullet 10^{+00}$	$9.32 \bullet 10^{-01}$	$9.29 \bullet 10^{-01}$
Water-Water	No. 1	$1.22 \bullet 10^{+02}$	$1.22 \bullet 10^{+02}$	$1.23 \bullet 10^{+02}$	$1.23 \bullet 10^{+02}$	$1.24 \bullet 10^{+02}$	$1.24 \bullet 10^{+02}$
	No. 2	$1.61 \bullet 10^{+00}$	$1.62 \bullet 10^{+00}$	$1.39 \bullet 10^{+00}$	$1.38 \bullet 10^{+00}$	$7.47 \bullet 10^{-01}$	$7.42 \bullet 10^{-01}$
R32	No. 1	$1.23 \bullet 10^{+02}$	$1.22 \bullet 10^{+02}$	$1.21 \bullet 10^{+02}$	$1.21 \bullet 10^{+02}$	$1.20 \bullet 10^{+02}$	$1.20 \bullet 10^{+02}$
	No. 2	$4.21 \bullet 10^{+00}$	$3.73 \bullet 10^{+00}$	$2.61 \bullet 10^{+00}$	$2.98 \bullet 10^{+00}$	$2.22 \bullet 10^{+00}$	$2.28 \bullet 10^{+00}$
R410a < 35 kW <sub>th</sub>	No. 1	$1.35 \bullet 10^{+02}$	$1.39 \bullet 10^{+02}$	$1.27 \bullet 10^{+02}$	$1.25 \bullet 10^{+02}$	$1.26 \bullet 10^{+02}$	$1.26 \bullet 10^{+02}$
	No. 2	$1.54 \bullet 10^{+01}$	$1.96 \bullet 10^{+01}$	$8.32 \bullet 10^{+00}$	$6.93 \bullet 10^{+00}$	$7.16 \bullet 10^{+00}$	$7.81 \bullet 10^{+00}$
R410a ≥ 35 kW <sub>th</sub>	No. 1	$1.25 \bullet 10^{+02}$	$1.27 \bullet 10^{+02}$	$1.24 \bullet 10^{+02}$	$1.23 \bullet 10^{+02}$	$1.24 \bullet 10^{+02}$	$1.24 \bullet 10^{+02}$
	No. 2	$5.99 \bullet 10^{+00}$	$8.68 \bullet 10^{+00}$	$5.56 \bullet 10^{+00}$	$4.87 \bullet 10^{+00}$	$5.43 \bullet 10^{+00}$	$6.01 \bullet 10^{+00}$
R410a (for BW HPs)	No. 1	$1.30 \bullet 10^{+02}$	$1.28 \bullet 10^{+02}$	$1.26 \bullet 10^{+02}$	$1.24 \bullet 10^{+02}$	$1.25 \bullet 10^{+02}$	$1.22 \bullet 10^{+02}$
	No. 2	$9.71 \bullet 10^{+00}$	$7.74 \bullet 10^{+00}$	$7.43 \bullet 10^{+00}$	$5.43 \bullet 10^{+00}$	$6.54 \bullet 10^{+00}$	$4.10 \bullet 10^{+00}$
R134a	No. 1	$1.26 \bullet 10^{+02}$	$1.27 \bullet 10^{+02}$	$1.26 \bullet 10^{+02}$	$1.25 \bullet 10^{+02}$	$1.26 \bullet 10^{+02}$	$1.26 \bullet 10^{+02}$
	No. 2	$7.08 \bullet 10^{+00}$	$8.21 \bullet 10^{+00}$	$7.59 \bullet 10^{+00}$	$6.57 \bullet 10^{+00}$	$7.84 \bullet 10^{+00}$	$7.84 \bullet 10^{+00}$

**Table 7**  
Deterministic results for power-appliance mass correlations (scope No. 2).

Technology	Nominal power	Impact category	Partial assessment –Variation (scope No. 2)
Air-Air	5.00 kW	Climate change	−1.32%
Air-Water	34.80 kW	Climate change	−3.66%
		Ozone depletion	−1.22%
		Eutrophication marine	−1.15%
		Land use	−1.44%
	592. kW	Climate change	1.17%

this article fixed equal to 3.5 for all the technologies; (ii) the climate profile of the electricity used to power the machine, in this case, the Italian electricity grid (evaluated equal to 423 gCO<sub>2</sub>eq/kWh<sub>el</sub>); (iii) the refrigerant gas used for the vapor compressor cycle and its leakages (in the article R32, R410a, and R134a with a leakage of 2% per year during the use phase), and (iv) whether the machine was correctly sized with respect to the theoretical building load (energy needs).

Table 7 summarizes the validation (deterministic) for the HP technologies assessed. The table reports: (i) in the first column the technology; (ii) in the second column the capacity values for which the test was performed; (iii) in the third and fourth the impact category – to avoid redundant data, the authors highlighted only those case studies where the indicators differed by more than 1.0% in absolute value; and (iv) in the fifth column the system boundaries analyzed – scope No. 2, excluding the use phase (electricity consumptions and refrigerant gas, i. e., charge, leakages, transports, and end-of-life treatments). The outcomes for scope No. 1 are not listed in Table 7 because they are below the threshold (<1.0%). For each Impact Category (IC), a variation value in percentage [%] was calculated using equation (8):

$$Variation_{ij} = \frac{IC \text{ for } mass_{f,ij} - IC \text{ for } mass_{d,ij}}{IC \text{ for } mass_{d,ij}} \quad (8)$$

Where (i) is the impact category under analysis among the 16 provided with the EF 3.1 EN15804 method, (j) is the technology (i.e., typology of HPs and refrigerant gas), (f) and (d) are the subscripts used for forecasted and declared masses.

All the variation values are less than 4%, therefore, negligible. Tests conducted excluding the use phase showed variations in Climate Change (CC), Eutrophication Marine (EM), and Land Use (LU) due mainly to the incidence of metallic materials (steel and copper) in the components production phase. Steel is responsible for the variations in CC; the variation in EM and LU is caused by copper production. Notably, the Climate Change (CC) impact category returned high variability (maximum value equal to 3.66% for Air-Water with 34.80 kW).

Fig. 6 shows graphically the outcomes achieved for the mass of refrigerant gas-capacity correlations using the same procedure. In this case, the partial evaluation (scope No. 2) was inferred by isolating the exclusively gas-related processes over the entire life cycle from those

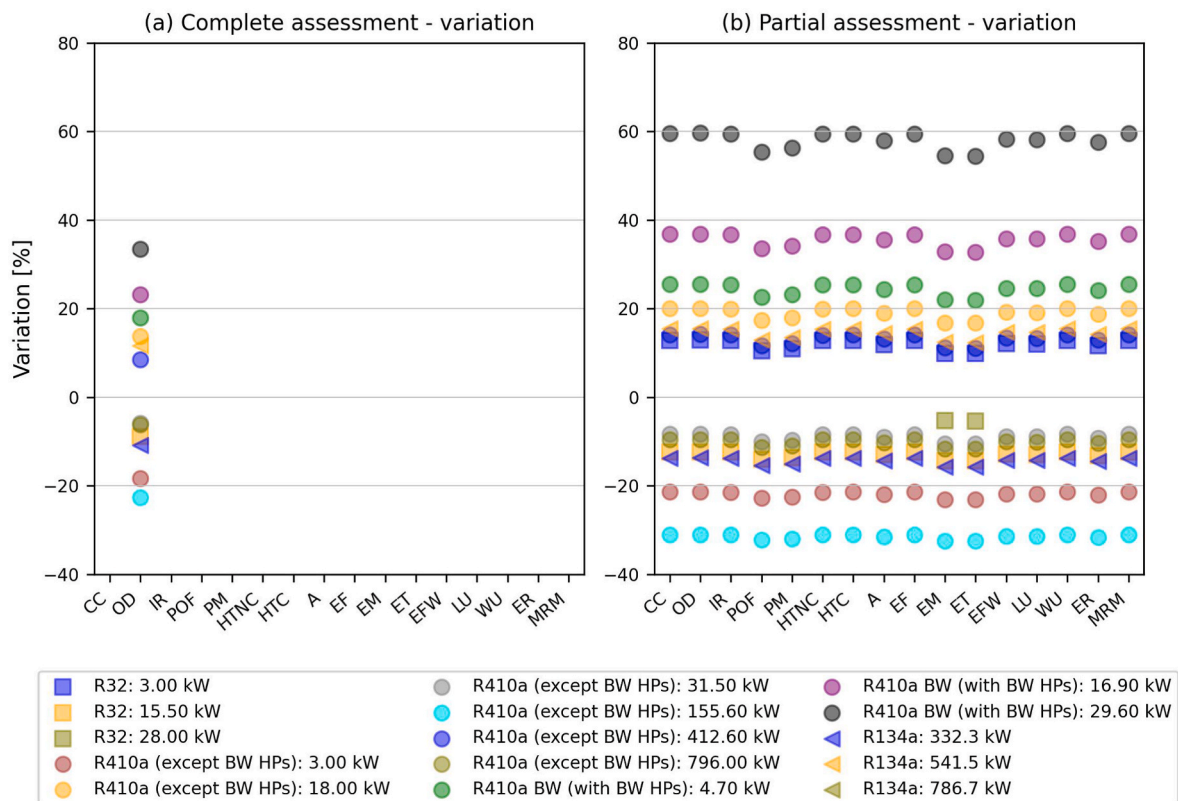


Fig. 6. Deterministic results for charges of refrigerant - power correlations: (a) Complete assessment - scope No. 1 and (b) Partial assessment - scope No. 2.

inherent in the machine. The figure shows only values that differed by more than  $\pm 5.0\%$ , having higher variability than Table 7. All tests for the complete assessment (scope No. 1) reported significant variations in Ozone Depletion (OD), up to 33.50% (R410a on brine-water big size) in absolute value due to the gas production process in the component production phase. LCA analyses conducted on a partial life-cycle assessment (scope No. 2) reported remarkable variations among indicator results. They range, in absolute value, from 2.94% to 13.69% (R32), 8.30%–59.65% (R410a), and from 0.00% to 15.72% (R134a). The variations are strictly linked with the amount of charge of the refrigerant gas forecasted.

It is important to consider that the reported values (Table 7 and Fig. 6) are related only to the tests conducted; variations are unrelated to the most significant impact category, being Material Resources: Metals/minerals (MRM) for capital equipment (Famiglietti et al., 2023).

### 3.3. Stochastic results

This section reports the stochastic results (uncertainty analysis based on error propagation) obtained. The Probability Density Function (PDF) and the confidence bound of the model outputs calculated by the stochastic method can be seen as measurement errors (Saltelli and Annoni, 2010).

Table 8 presents the outcomes where the alternative hypothesis test was not rejected for power-charge of refrigerant correlations (complete assessment – scope No. 1). Therefore, the table reports the cases in which the test is not verified in line with the thresholds indicated in section 2.3 ( $\alpha$  lower than 0.35 and  $\beta$  higher than 0.15, with a significance level of 0.05). The probability of committing a Type II error over the threshold was assessed for the Ozone Depletion impact category for HP appliances using R32 and R134a, respectively. For the R410a, the probability of committing a Type II error is extended to the Climate Change impact category for HPs with a capacity lower than 160 kW<sub>th</sub>. In some cases, the coefficients reported in Table 8 reached 0.0 and 0.0 for Type I and II,

meaning that the two PDFs obtained with the Monte Carlo analysis do not overlap, with no probability of committing a Type I error (the results are different). The outcomes align with the deterministic (Fig. 6), highlighting a higher variation in the Ozone Depletion impact category than the others. Considering the partial assessment (scope No. 2), the correlations are unreliable: the  $\alpha$  and  $\beta$  coefficients are lower than 0.35 and over 0.15 for many impact category indicators, respectively. Vice versa, the stochastic outcomes were all verified for power-appliance mass correlations ( $\alpha$  higher than 35% and  $\beta$  lower than 15% for all the analyses implemented). The  $\alpha$  and  $\beta$  coefficients were presented in the supporting material Microsoft Excel files “Monte Carlo” and “Hypothesis test” to avoid redundant data.

The authors point out important aspects for the purpose and objective of the study, defining the domain of using the family correlations created (power-appliance mass and power-refrigerant gas charge):

- power-appliance mass correlations are reliable and can be used for each impact category evaluation and for both the scopes defined linked with the system boundaries (complete and partial assessment);
- power-charge of refrigerant correlations related to R32 and R134a can be used for carbon footprint analysis for both scopes. The impact category is always verified according to the hypothesis test for all the capacity sizes;
- R32 and R134a power-charge of refrigerant correlation is reliable considering scope No. 1 (complete assessment) for all impact categories and capacities (except for Ozone Depletion). This kind of application is feasible for urban-scale software, where many heat pumps are evaluated on a large scale without the need to assess individual components or life cycle stages in detail. For this type of application, the correlations can also be used for big appliances R410a (above 160 kW<sub>th</sub>).

**Table 8**  
Stochastic results for power-charge of refrigerant correlations.

Technology	Test	Impact category	Complete assessment – scope No. 1	
			P(Type I error)	P(Type II error)
R32	3.00 kW <sub>th</sub>	Ozone Depletion	0.00	0.00
	28.00 kW <sub>th</sub>	Ozone Depletion	0.17	0.28
R410a (P ≤ 35 kW <sub>th</sub> )	3.00 kW <sub>th</sub>	Climate Change	0.00	0.00
		Ozone Depletion	0.00	0.00
	18.00 kW <sub>th</sub>	Climate Change	0.28	0.19
		Ozone Depletion	0.00	0.00
	31.50 kW <sub>th</sub>	Climate Change	0.43	0.13
		Ozone Depletion	0.00	0.00
R410a (P > 35 kW <sub>th</sub> )	155.60 kW <sub>th</sub>	Climate Change	0.03	0.39
		Ozone Depletion	0.00	0.00
	412.60 kW <sub>th</sub>	Ozone Depletion	0.00	0.00
		Ozone Depletion	0.00	0.00
R410a brine-water	4.70 kW <sub>th</sub>	Climate Change	0.07	0.44
		Ozone Depletion	0.00	0.00
	16.90 kW <sub>th</sub>	Climate Change	0.04	0.47
		Ozone Depletion	0.00	0.00
	29.60 kW <sub>th</sub>	Climate Change	0.28	0.19
		Ozone Depletion	0.00	0.00
R134a	332.30 kW <sub>th</sub>	Ozone Depletion	0.00	0.00
	541.50 kW <sub>th</sub>	Ozone Depletion	0.00	0.00
	786.7 kW <sub>th</sub>	Ozone Depletion	0.34	0.16

#### 4. Conclusions

In this work, the authors create 5 empirical correlations (mass-nominal power laws) concerning electric heat pumps technologies (vapor compression), classified as (i) air-air (No. 1 correlation), (ii) air-water (No. 2 correlations), (iii) brine-water (No. 1 correlation), and (iv) for water-water (No. 1 correlation), considering the cold source and the carrier used for the distribution of the heat within the building. The authors also implemented 5 empirical correlations for refrigerant gases used by machines, providing the amount of charge in the function of the nominal capacity for the appliances using R32 (No. 1 correlation), R410a (No. 3 correlations), and R134a (No. 1 correlation). The refrigerant gas R32 was never investigated before. The algorithms were created using information published in the Conto Termico database (considered representative of the Italian market) and integrating missing information from technical datasheets provided by the manufacturers on their websites. 17 745 heat pumps were collected and described for: (i) typology of operation, (ii) exchange typology, (iii) thermal capacity, (iv) Coefficient of Performance, (v) mass, (vi) typology of refrigerant gas, and (vii) mass of the gas refrigerant. The validation of the correlations was conducted following a deterministic (without uncertainty analysis) and a stochastic approach (with uncertainty analysis based on error propagation), deriving the following conclusions for the machines sold in Italy:

- power-appliance mass correlations are reliable and can be used for each impact category evaluation, and both the scopes defined are linked with the system boundaries (complete and partial assessment) and for all the impact categories considered;
- power-charge of refrigerant correlations related to R32 and R134a can be used for carbon footprint analysis for both scopes;
- R32 and R134a power-charge of refrigerant correlation is reliable considering scope No. 1 (complete assessment) for all impact categories and capacities (except for Ozone Depletion).

Moreover, the outcome of this work could be further improved with a large amount of primary data and extended covering other technologies (i.e., natural gas boilers, gas-absorption heat pumps, etc.). Other potential improvements could be in collecting more data related to the life cycle inventory of the electric heat pumps. To date, the relative mass

contribution of each component was estimated from three different publications (Greening and Azapagic, 2012; Heck, 2007; Kemna et al., 2019), assuming a constant split of the mass fractions of the whole equipment in changing the nominal power (i.e., steel, copper, aluminum, etc.). A greater collection of primary data would make it possible to create more robust parameterization factors, allowing the total mass of the machine (obtained through the empirical correlations shown) to be broken down more consistently, reducing the uncertainty of the final results provided.

#### CRedit authorship contribution statement

**Kevin Autelitano:** Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft. **Jacopo Famiglietti:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Validation, Visualization, Writing – original draft, Writing – review & editing, Supervision, Project administration. **Tommaso Toppi:** Investigation, Methodology, Validation, Writing – original draft, Supervision. **Mario Motta:** Supervision, Project administration, Funding acquisition.

#### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

#### Data availability

Data will be made available on request.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.cesys.2023.100135>.

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