Including EAHX (earth-to-air heat exchanger) in early-design phases considering local bioclimatic potential and specific technological requirements

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Abstract. Horizontal ground systems for ventilative cooling/heating, such as earth-to-air heat exchangers (EAHX), are a valid pre-heating and pre-cooling low-energy techniques to reduce the building energy consumptions for space heating and cooling. Nevertheless, the potential of these systems, such as others passive solutions, is local specific and need for devoted design methodologies. In particular, EAHXs need to be included in the design process as soon as possible in order to maximise the potentiality and allow for their integration – operational, technological and environmental issues. The paper will introduce a design methodology to define the local climatic potential of EAHX since the building programming phase by defining specific boundary conditions in well-known bioclimatic chart instruments. The effect of different design choices will be analysed for a set of three representative Italian locations. Furthermore, main functional, operational and environmental requirements will be discussed for this technical system. This analysis is based on the performance-drive approach to environmental and technological design – see for example UNI 8290-2:1983 – and is hence compatible with the technological-design practice and early-design consolidated methodologies.

1. Introduction
Buildings have a recognised impact on total energy consumptions and related amount of emitted GHGs [1]. Several alternative solutions, able to reduce the energy needs without compromising the comfort quality, are included in current standards towards the nZEB/ZEB building stock vision by also encouraging the diffusion of renewable sources. However, the adoption of natural cooling solutions is still very limited. This is due to two main aspects: i) low-energy cooling systems, based on natural heat sinks (air, water, ground, and night sky), have a local specific applicability [2] that needs to be defined by KPI (key performance indicators); ii) there is a lack of simple design methodologies to include these systems since the building programming phase. This paper focuses on EAHX (Earth-to-Air-Heat-Exchanger), a ventilative low-energy cooling and heating system based on horizontal buried pipes. This technique is very effective, but not well known by designers. The paper aims at defining a method to support early-design choices and building-integration strategies to include EAHX systems from the building programming design phase (preliminary design), a phase in where the potential for integrating renewable sources and bioclimatic design aspects is maximal and the changing cost minimal – for a definition of building programming see [3].

2. Methodology
The proposed approach is based on a performance-driven methodology organised around feed-back cycles connecting user activities with performances. The process is based on the definition of a list of requirements – i.e. technical transposition of needs connected with the building process (UNI 8290-2:1983) – and further checking and optimisation of the environmental and technical units’ performances following the logical line: users → activities → needs → requirements ← performances. This specific
design approach is well-known and defined since the 60’s – e.g. for the Italian context see [4] and standards such as the UNI 7867-4:1979, substituted by the UNI 10838:1999 (terminology), the UNI 8290-1:1981, 8290-2:1983, 8290-3:1987, 8289:1981 (need classification), and the UNI 11277:2008.

The EAHX design method here introduced can be divided into three parts. Firstly, the EAHX system is split up into technical elements in order to analyse them both independently and as regards their interrelations. All elements are analysed for functional, operational and environmental requirements in order to define boundary conditions and possible integration strategies (see §3.1.). Secondly, the required amount of installation land is calculated or adapted according to the available plot area – see §3.2.. Finally, a potential list of indicators is reported in order to check the local climatic potential and suggest potential optimisation strategies – by using feed-backs – considering the expected energy exchange due to EAHXs – see previous works, Ref. [5,6].

This last step of the methodology is related to local climate and allows optimising EAHX integration in building design since early phases by fulfilling the previous two steps with quantitative data. For this reason, a discussion session on these last indicators is produced considering a set of 3 representative locations for Italian climate context and a series of variations in design inputs (tube length, diameter, depth) and in climate conditions in order to test the resilience of this technology – in terms of geo-climactic potential – under the effect of climate changes. Previous analyses demonstrate the importance of this type of study [7], especially to analyse the expected increase in the cooling energy demand [8]. For climate changes, 3 different IPCC scenarios were used (B1;A1B;A2) referring to a low, medium and high impact scenarios, compatible respectively with the recent RCP 4.5, 6.0 and 8.5.

3. EAHX early-design approach

3.1. EAHX technical elements and related requirements

Several parameters are related to the design of an EAHX system and in particular, from the design point of view, the following: the diameter of the buried ducts, the air velocity, the number of parallel tubes, the material used for the pipes (e.g. stiffened polyethylene with mould and rat prevention treatments), installation depth, tube length, terrain type and thermal characteristics, typical local weather conditions, site-boundary effects, distance between parallel pipes, distance from the EAHX system, the building or other buried systems (e.g. district heating) – these distances eliminate mutual interferences –, ground water level, system geometries in order to reduce the pressure losses, and the height of the inlet grid to prevent animal and dust entrance (though dust filters and grid are recommended). For the effect of the climate-related variables, see also the description in [5]. Nevertheless, EAHX systems may be decomposed in technical elements to which these parameters can be directly connected. In particular, it is possible to list the following main classes of elements: a. intake, b. exchangers or buried pipe(s), c. toward building distribution. Furthermore, according to the type of system (single tube, multi-tube, or multi-fields), these classes will include the following technical elements: (a) intake (captation), inlet mixing chamber, distribution channel; (b) parallel buried pipes; (c) collecting channel, condensation and drainage chamber, mixing chamber (multi-fields), mixing with external air with external air intake, building distribution or connection to AHUs. A first functional, operational and environmental list of requirements is reported in Table 1 for a single tube case with fan-airflow activation (after EAHX). A longer list including multi-fields and different building distribution cases is also under development.

| Table 1. Functional, operational and environmental requirements for the early-design of EAHX systems (single tube system with fan activation) |
| --- |
| Technical element | Functional requirements | Operational requirements | Environmental requirements |
| a. intake | - positioned at least 1.5 m from ground level to reduce the risk of dust entering - made in concrete or plastic materials, be careful to minimise the pressure drop in the two curves | - intake vents far from airflow obstacles to reduce the risk of additional pressure drops - dust filter must be replaced periodically (has to be accessible) | - position the intake in a shaded summer or sunny-winter area - expose the intake air vent to prevalent winds (especially for... |
3.2. EAHX required installation land

**Figure 1.** Simplified procedure to estimate the number of parallel tubes and the required space to install the EAHX system in early design phases.

The distance between the tubes and the actual number of tubes, with the consequent effect on the amount of free land to be devoted to the system, can be easily estimated by using the procedure developed in [9]...
and here summarized in the scheme of Fig. 1. Firstly, according to the operational mode of EAHX, i.e. in summer: cooling + IAQ (Indoor Air Quality); in winter: IAQ only, the required airflow rate is calculated – e.g. for IAQ using minimum airflow rate for the number of people or square meters according to the building type, see for example minimal ventilation rates defined in EN 15251:2007 –. Secondly, the total net area of tubes is established by fixing a designed air velocity in the tubes (e.g. 2 m/s). Thirdly, by fixing the tube diameter (e.g. 30 cm), it is possible to calculate the minimum number of tubes to be installed in the plot. The distance between tubes and the tube lengths will be used in the end to define the space required to install the designed EAHX system. The early-defined EAHX-system occupation can be further optimised according to the proposed geo-climatic potential KPIs introduced in [5] and described in the further section by adopting a feedback procedure.

3.3. EAHX geo-climatic potential

The effectiveness of EAHX ($\varepsilon_{\text{eahx}}$) is function of the following main aspects [2,5,10-11]: soil characterisation (thermal parameters), system characterisation (installation depth, tube length, diameter and material) and operational mode (air flowrate). The main thermal source or sink is characterised by the temperature of the soil near the pipe wall ($\vartheta_{\text{soil,h}}$). This value can be estimated, for undisturbed soil, by using the Labs’ expression [12] knowing soil thermal diffusivity, the average soil-surface temperature, its annual semi-amplitude variation, the phase shift constant, and the EAHX depth (h). These last 3 values may be calculated by using the auxiliary software CalcSoilSurfTemp of EnergPlus [13], or simplified methods [6], while the soil diffusivity can be taken by tabular databases [9]. It is hence possible to estimate the treated EAHX air temperature ($\vartheta_{\text{eahx}}$) by assuming the inlet temperature ($\vartheta_{\text{in}}$) from TMY (typical meteorological year) – see expression (1):

$$\vartheta_{\text{eahx}} = \vartheta_{\text{in}} - \varepsilon_{\text{eahx}} (\vartheta_{\text{in}} - \vartheta_{\text{soil,h}}) \ [\degree C]$$

(1)

Furthermore, since the outlet-air RH% (relative humidity) is not known, it is possible to define the vapour quality of the treated air (X) assuming it equal to the one of the inlet air, which is calculable by using well-known psychrometric methodologies, such the one described in [5], by calculating the saturated vapour pressure using [14]. To consider potential summer condensation phenomena, the correspondent outlet RH% will be derived and vapour value re-fixed if RH% overpass 100%.

Calculated the expected outlet air temperature from an EAHX system for each TMY hours, it is possible to evaluate comfort conditions. For the purpose of this paper, the Givoni-chart comfort boundaries were assumed [15-16] to analyse the environmental air and the EAHX-treated air and calculate the number of discomfort hours in both cases. The percentage of hours in where environmental discomfort is turned to comfort by EAHX is assumed as geo-climatic KPI (key performance indicator) for this analysis. Moreover, the percentage of hours in where EAHX may reduce the discomfort without reaching comfort conditions is also defined, because EAHX is especially used as pre-treating technology. This analysis considers both temperature and humidity comfort conditions. Finally, since the sensible pre-heating and cooling potential will not be evaluable by these KPIs, the percentage of the reduction in HDD (Heating Degree Days) and CDD (Cooling Degree Hours) will be used as KPI to represent the potential reduction in the cooling and heating expected demand by adapting the heating and cooling degree day indexes to calculate also their residual version [17]. HDH_{res} and CDH_{res} are calculated in accordance to [6] assuming a base temperature of 18.3°C for the heating season, in accordance to ASHRAE Fundamentals, and 22°C for the cooling season [18]. The number of hours in where EAHX may bring discomfort temperature conditions to comfort ones is also calculated by using the same base seasonal temperatures as set points. Considering the early-design stage, this analysis is performed at climate level, like in Givoni-chart studies, and for this reason any specific building is already considered. Nevertheless, a preliminary balance of these results with respect to the required airflow for cooling can be calculated by adapting the methodology reported in Ref. [9].

4. Discussion on the geo-climatic potential

The proposed method is here applied to 3 sample locations representative of different Italian climates: Turin (north west of Italy; Cfa; HDD$_{18.3}$ 2560; CDD$_{22}$ 190), Rome (centre; Csa; 1668;365), and Palermo (south; Csa; 822; 430). Relative TMY were produced by Meteonorm v.7.1 considering the range 1991-
00 for irradiation and 2000-09 for temperatures. An EAHX effectiveness of 0.6 is assumed as reference for this first analysis assuming a sample EAHX system of 50m in length, 25cm in diameter, 2.5m in depth, a heavy and damp soil (diffusivity 6.45*10⁻⁷ m²/s²), and an air velocity of 1.4 m/s (247 m³/h) – see [5]. Figure 2(a) reports the percentage of hours turned to comfort by EAHX in each location together with the percentage of hours in where EAHX may contribute to reduce the discomfort. Figure 2(b) shows the reduction percentages of HDD and CDD due to EAHX for the same locations together with the reduction percentage of discomfort hours in heating and cooling mode considering as comfort threshold the defined base temperatures. These graphs underline that EAHX principally works as pre-treating solutions with a good potentiality in Italian climate conditions – see also [19]. This technique has a very good potential in reducing the sensible heating needs, even if in winter EAHXs only rarely reach directly comfort conditions. It is also underlined a good potential in reaching temperature set-point comfort conditions in summer, even if the sensible nature of the heat exchange may cause an increase in the RH% discomfort.

Figure 2. (a) percentage distribution of yearly hours according to comfort-Givoni chart boundaries including EAHX effects; (b) percentage reduction of environmental HDD and CDD by EAHX – bars – and of discomfort hours considering the sensible base temperature limits – points.

Figure 3. Palermo case, different design choices: (a) changes in the percentage distribution of hours according to Givoni comfort boundaries; (b) percentage reduction of the HDD and CDD by EAHX

Figure 4. (a) percentage distribution of yearly hours according to Givoni-chart comfort boundaries including EAHX effects; (b) percentage reduction of environmental HDD and CDD by EAHX
Nevertheless, a sensitivity analysis was also produced in order to analyse the potential effect of different design choices on the sample reference case. Length has been changed in the domain \( \{25;50;75\text{m}\} \), pipe diameter in \( \{0.15;0.25;0.35\text{m}\} \) and depth in \( \{1.5;2.5;5\text{m}\} \). Furthermore, air velocity varies in the domain \( \{1.4; 2.8; 4.2\text{m/s}\} \). Relative effectiveness values for these configurations were desumed by literature [5]. Small changes were underlined when the Givoni-chart comfort boundaries are assumed. Differently, when we compare the reduction in percentage of the ambient HDD and CDD due to EAHX, changes were evident. It can be stated that lower lengths and depth will reduce the effect on the outlet temperature, such as expected, while higher velocity will also reduce this difference in temperature, even if this choice allows to treat a higher amount of air and hence may arrive to higher power exchanges – a variable not here considered. Fig. 3 reports this analysis for Palermo.

Finally, considering the climate-dependent nature of this study, an analysis is presented to define the variations of the used KPIs when different TMY sources are assumed: 1.an ancient TMY, in respect to the reference one, reference period 1981-90 (irradiation) and 1961-90 (temperatures); 2.the reference case; 3.potential future TMY, year 2050, considering 3 IPCC scenarios (B1; A1B; A2). These last cases were produced using the Meteonorm elaboration engine [20]. These climate data were applied to the base configuration to underline potential variations. Figure 4 shows (for the case of Turin and Rome) the climate-induced variations. An increase of EAHX potential activation hours is underlined, while, on the percentage of reduction of DD indexes an increase in the heating potential is evident together with a decrease in the cooling one because of related environmental trends: increase in the environmental temperatures with consequent growth of environmental CDD and reduction in environmental HDD.

5. Conclusions

The paper reports a simple approach to include EAHX systems since early-design phases considering: i) environmental operational and technological lists of requirements, ii) a simple approach to define the needed installation land according to building airflow requirements, and iii) a method to define the local potential of the system including Givoni-comfort chart turned to comfort hours, reducing discomfort hours and potential reduction in the local HDD and CDD indexes. The application to a sample set of Italian climates show the expected influence of different design configurations and climate change scenarios on the local EAHX potential.

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