

RESEARCH REPORT



Earth Tube Ventilation Systems - Applicability in the Canadian Climate



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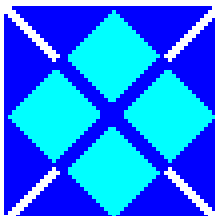
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Abstract

This report summarizes the results on a study on residential earth-to-air heat exchangers (EAHX, also called earth tubes) and their applicability to the Canadian climate. The project analyzed over 45 publications on the subject, and identified close to 30 Canadian residential installations. The information gathered from these various sources was synthesized to identify trends in energy performance, indoor air quality implications, design and construction features and system costs, etc.; general conclusions regarding the performance of earth tube systems, their applicability, and their suitability, were drawn.

This study has shown that EAHX may have benefits when used under the right conditions and in the right climate, but also that they are very subtle systems which require careful design and operation to be successful. Controls, air quality, and thermal memory of the ground are but three of the areas to be concerned about when considering whether an EAHX is worth it. One also needs to be aware that there is little advantage in using EAHXs in series with heat recovery ventilators, and that the economics are rarely favourable.

The performance of EAHX in most of Canada's climatic conditions has not yet been demonstrated through validated rigorous energy and indoor air quality monitoring. Until such data can be obtained, the findings from this project need to be carefully evaluated prior to undertaking any such installation.

Table of Contents

Executive summary.....	2
1 Introduction	5
1.1 Background	5
1.2 What this report contains	5
1.3 Acknowledgements	7
2 Literature search, Manufacturers, Design tools	8
3 Summary of existing systems	9
3.1 Canada	9
3.2 Earth tube systems in the USA	18
3.3 Use of earth tubes in other countries	19
3.4 Brine based systems	21
4 Synthesis.....	22
4.1 Current accomplishments.....	22
4.2 Open questions	23
4.2.1 Lack of monitored data	23
4.2.2 Controls	23
4.2.3 Long-term temperature imbalance in ground	24
4.2.4 Air quality	24
4.2.5 Interaction with the rest of the building	25
4.3 EAHX and HRV	25
4.4 Economics.....	26
4.5 Applicability of EAHX	26
5 Conclusion	27
6 Appendix A: Annotated bibliographic summary.....	28
6.1 Scientific papers and publications.....	28
6.2 Books, manuals, and norms.....	41
6.3 Internet resources.....	43
7 Appendix B - System manufacturers	45
8 Appendic C - Software	48
9 Appendix D - ASHRAE Climate zones.....	49

Executive summary

Canada Mortgage and Housing Corporation (CMHC) initiated in 2010 a study to research the availability of valid information on earth tube ventilation systems (also called Earth to Air Heat Exchangers or EAHX) and their applicability in the Canadian climate. The focus of the study was residential systems. The objectives were:

- To research information on actual, monitored performance of existing residential earth tube systems in Canadian climate conditions, including: energy savings, indoor air quality, design and construction, and costs.
- To synthesize the information to formulate broad conclusions regarding the performance of earth tube systems in Canada.

Close to 30 Canadian residential systems in existence or being built were identified, as well as nearly 10 more in the commercial sector. Knowledge about the systems was gained through discussions and email exchanges with their designers or operators. These discussions were complemented by a large literature search. Given the small size of the Canadian stock, the study was extended to include systems from the USA and more importantly Europe, where hundreds if not thousands of systems have been deployed.

European experience shows that EAHX may have benefits when used under the right conditions and in the right climate, but also that they are very subtle systems which require careful design and operation to be successful. The literature shows that an improperly designed system will not work as expected, or result in poor air quality, etc. leading to disenchantment with the system and in many cases decommissioning, as it is often very difficult to fix EAHXs once the trenches are back-filled.

The literature also shows that controls, air quality, and thermal memory of the ground are but three of the areas to pay close attention to when considering an EAHX. It also demonstrates that EAHX are redundant when used in conjunction with heat recovery ventilators (HRV), and that the economics are rarely favourable.

The absence of comprehensive research, testing and analysis on the performance of EAHX systems makes it difficult for prospective users to assess whether or not EAHX systems are appropriate for any given installation. The performance of EAHX in most of Canada's climatic conditions has not yet been demonstrated through validated rigorous energy and indoor air quality monitoring. Until such data can be obtained, the findings from this project need to be carefully evaluated prior to undertaking any such installation.

Résumé

En 2010, la Société canadienne d'hypothèques et de logement (SCHL) a commandé une étude qui avait pour objet d'étudier la disponibilité d'informations valables sur les installations de ventilation géothermique (aussi appelées échangeurs de chaleur air-terre) et leur applicabilité, compte tenu des conditions climatiques sévissant au Canada. L'étude était axée sur les installations résidentielles et avait pour objectifs de :

- Rechercher des données sur la performance réelle et suivie d'installations de ventilation géothermique existantes dans des conditions climatiques canadiennes, notamment sur les économies d'énergie, la qualité de l'air intérieur, la conception, la construction et les coûts;
- Synthétiser l'information de manière à formuler des conclusions générales sur la performance de la ventilation géothermique au Canada.

Près de 30 installations résidentielles existantes ou en construction ont été trouvées au Canada, en plus de 10 autres dans le secteur commercial. Des renseignements au sujet de ces installations ont été recueillis grâce à des discussions et à des échanges de courriels avec leurs concepteurs ou exploitants, et une vaste recherche documentaire a été réalisée. Comme on trouvait peu d'installations de ce genre au Canada, l'étude a dû être étendue aux États-Unis, mais surtout à l'Europe, où des centaines voire des milliers de systèmes du genre ont déjà été mis en place.

L'expérience européenne nous apprend que la ventilation géothermique peut s'avérer avantageuse lorsqu'elle est utilisée à bon escient et dans les bonnes conditions climatiques, mais aussi qu'il s'agit d'installations très sensibles qui demandent une conception et une exploitation soignées pour produire de bons résultats. La documentation montre que les installations mal conçues ne fonctionneront pas comme prévu, ou produiront une piètre qualité de l'air intérieur ou d'autres problèmes, ce qui mènera au désenchantement et dans plusieurs cas à la mise hors service de l'installation. En effet, il est souvent très difficile de réparer une installation de ventilation géothermique une fois que les tranchées ont été remblayées.

La documentation révèle également que les commandes, la qualité de l'air et la mémoire thermique du sol ne sont que trois des facteurs sur lesquels il faut se pencher lorsqu'on envisage la mise en place d'un système de ventilation géothermique. Elle indique aussi que ces installations sont redondantes quand on les utilise en présence de ventilateurs récupérateurs de chaleur, et que les aspects économiques sont rarement favorables.

Pour les utilisateurs potentiels, l'absence de recherche concluante, d'essais et d'analyses détaillées sur la performance des installations de ventilation géothermique complique la tâche de déterminer si la ventilation géothermique convient à un aménagement donné. La performance des systèmes dans la plupart des conditions climatiques propres au Canada n'a d'ailleurs pas encore été démontrée par un suivi rigoureux en matière d'énergie et de qualité de l'air intérieur. En attendant que ces données puissent être obtenues, les constatations de la présente étude doivent être soigneusement évaluées avant d'entreprendre une telle installation.



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1 Introduction

1.1 Background

Earth tubes, also called earth-to-air heat exchangers (EAHX), ground-coupled heat exchangers, or earth channels, are long metallic, plastic or concrete pipes that are laid underground and are connected to the air intake of buildings (either houses or commercial buildings). Their purpose is to provide some pre-conditioning of the air – either pre-heating in the winter or pre-cooling in the summer; in some climates, the purpose can even be to provide summer cooling and dispense with a dedicated air-conditioning system. These systems received some attention¹ in the late 70's and early 80's but they did not end up enjoying wide acceptance, either because of lack of performance or because of other associated problems such as poor air quality (mold and bacterial growth in the tubes).

The current push towards a wider use of green technologies has generated a resurgence of interest in the concept of earth tubes. The systems are promoted as a simple and effective way to reduce the amount of greenhouse gases associated with the operation of buildings. However, the actual performance of these systems, particularly under Canadian climatic conditions, is not well documented. For that reason Canada Mortgage and Housing Corporation (CMHC) issued in July 2010 a Request for Proposal (RFP) to study information available on the performance of earth tube ventilation systems and their applicability in the Canadian climate, with the aim of filling this void by providing valid and unbiased information upon which builders and consumers can make informed decisions before using such systems. This report summarizes the work done by Numerical Logics Inc. in response to this RFP.

1.2 What this report contains

The focus of this report is EAHXs in the residential context in Canadian climatic conditions. EAHXs are found both in commercial/institutional/industrial buildings, and residential buildings. There are several important differences between the two categories of systems:

- systems in commercial buildings tend to be much larger since the buildings themselves are larger. Often the EAHX is made of large concrete pipes, whereas plastic tubes are used in residential systems;

¹ US Department of Energy Website, http://www.energysavers.gov/your_home/space_heating_cooling/index.cfm/mytopic=12460, accessed August 7, 2011.

- systems in commercial buildings tend to be more sophisticated, in particular in terms of controls, since they have dedicated personnel to operate them. By contrast, residential systems are meant to be operated by non-experts;
- commercial buildings tend to have very different load patterns than individual houses. They have often high internal gains and high needs for cooling. They tend to be occupied during daytime whereas houses are occupied all day.

Although the focus of this study is residential buildings, a few commercial buildings will be mentioned in this report. One reason is that very little monitoring has been done for residential EAHXs whereas data exists for commercial buildings in greater quantity and quality. Furthermore, as will be seen, the operation of EAHXs in commercial buildings sometimes revealed problems which are likely to exist in residential buildings as well. Commercial systems are therefore included in this study because of the lessons that can be learned from them and applied to residential systems, in particular in terms of controls and, to some extent, in terms of energy gains.

With this in mind, the work presented in this report proceeded in several directions:

- A bibliographic search was conducted (section 2 and Appendix A). It focused mostly on articles that contain monitoring results, although some articles focus on controls or simulation. Most of them are for systems outside North America, since EAHX systems are more frequent in Europe. Systems outside of Canada were matched to Canadian regions with similar climate conditions through the use of ASHRAE climate zones (see Appendix D). Note that climate zones are based on degree-days and represent only an approximation of the climate; it does not include all aspects of climate which may affect the actual performance of earth tubes. Appendix B also presents information about commercial systems from France, Germany, Switzerland, Belgium, and Japan, and Appendix C provides a short summary about design tools.
- Several Canadian systems were identified (section 3.1). The amount of information that could be obtained varies greatly from system to system. Since actual system performance was sought, a few additional systems outside of Canada were also listed (sections 3.2 and 3.3).
- Finally, the information gathered from these various sources was synthesized to identify trends in energy performance, indoor air quality (IAQ) implications, design and construction features and system costs, etc.; general conclusions regarding the performance of earth tube systems, their applicability, and their suitability, were drawn (section 4).

The report focuses mainly on earth to air heat exchangers. A competing design replaces the air tubes with a glycol or brine loop with a heat exchanger located at the entrance of the heat recovery unit. A few words will be said about these systems (section 3.4) but they are not covered extensively in the report.

1.3 Acknowledgements

During the course of this research, a number of individual and companies were contacted. I would like to thank the following people who have provided very valuable information about EAHXs (in alphabetical order by first name):

Aaron Obrigewitsch, Craik Ecovillage (SK)
Alain Hamel, A & A Construction (QC), www.aetaconstruction.com
Alexandre Thibodeau, AT architecture & construction (QC), at-ac.ca
Boris Lamontagne, maison Auclair-Lamontagne (QC)
Broadway Architects (BC)
Bruno Herzog, Batir Bio (France), www.batirbio.org
Charles Zaloum, CMHC (ON)
Chris Magwood, Fleming College (ON), www.flemingc.on.ca
Christopher Fox and John Kimball, Rehau (USA/Canada), www.rehau.com
Dale Wilker at Quiniscoe Homes, quiniscoe.ca
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Emmanuel Cosgrove, ecohabitation.com (QC)
Frank Bassett, Electronic Arts (BC), www.ea.com
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Jens Pfafferott, Fraunhofer Institut (Germany), ise.fraunhofer.de
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Ken Ruest, CMHC (ON)
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www.healthyheating.com
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Stéphane Thiers, MINES ParisTech (France), www.mines-paristech.fr
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Thomas Füchs, Hegler (Germany), www.hegler.de
Trevor Butler, Archineers, archineers.com (BC)
Vic Ellis, SCI Sustainable Concepts Inc. (SK)

I apologize for any omission in this list. Please note that the individuals above have no responsibility in the material contained in this report; the opinions expressed hereafter are only my own.

2 Literature Search, Manufacturers, Design Tools

An extensive literature search was conducted, both in English and in French, to assess the use, performance, and air quality of EAHXs. The search turned up many other papers which are not listed here. In particular, there are many papers which are solely devoted to simulation. While this is certainly of interest, this was not the focus of this study which is seeking to compile actual EAHXs results. There are often very significant differences between simulated and operating systems. For example thermal exchanges in the ground may be more complex than what is simulated; or the actual operation may deviate from idealized controls.

The search was limited only to relatively recent papers. Older papers from the 1980's and 1990's were often just discovering the complexity of EAHXs and missed a lot about the subtleties of their behaviour.

Finally the quantity and depth of the analysis of monitoring data in the literature was found to be limited. Most studies present a very limited amount of monitoring - for example, a system operated and monitored only a couple of days in each month; or a system operated every other day to show the differences between using and not using the EAHX. While these studies meant well and present useful results, they do not provide any indication of the long-term, year-round performance of the systems, which may be very different from what is observed in a short-term measurement. Similarly, some monitoring results characterized only the maximum temperature differential between inlet and outlet of the EAHX. While interesting, this measure does not provide any idea of the energy performance of the system unless the flowrate is well characterized too (to calculate energy collected, one requires both flowrate through the tube and temperature differential between outlet and inlet).

The papers relevant to this study are listed in Appendix A, along with a short summary of the most interesting points. Publications are listed in alphabetical order of first author.

The study also identified a number of manufacturers of pre-designed systems, and software tools that can be use to design and simulate EAHXs. These can be found in Appendices B and C, respectively.

3 Summary of existing systems

There are a number of earth tubes systems currently in operation in Canada, the USA, Europe, India, and Japan. The focus of this study was Canada so systems in this country were researched, and the ones below were identified. A few systems were located in the USA as well. When systems are located outside of Canada, ASHRAE climate zones will be mentioned; Appendix D enables to see which Canadian regions are located in similar climate zones.

The following section details the main characteristics of the earth tube systems, the availability of performance information and the designer's or owner's views on performance.

3.1 Canada

La Maison Leed d'Alexandre Thibodeau²

This pilot project of a LEED For Homes is located in Bolton Ouest, QC. It comprises an EAHX with two branches totalling around 70 m (230') in length. The 150 and 200 mm tubes are made of flexible plastic piping with smooth interior and corrugated exterior. System performance is not known at this stage as the system is not balanced yet (this is planned for summer 2011). The designer of the system, Alexandre Thibodeau, is looking for partners to monitor the system and evaluate its performance. If the system proves successful, the experience may be shared with potential Canadian partners interested in further commercial development of the pipe and control systems. Estimated price is around \$1,200-1,500.

Maison Auclair-Lamontagne³

This residence located in Aylmer, ON, was built in 2006. It is a very simple system to temper the air entering the house. PVC tubing with a diameter of 15 to 20 cm (6 to 8") is used. Prior to Nov. 2010 there was no mechanical fan pushing air through the tube; according to the owner, air was moving simply because of a negative pressure difference between the house and the outside. Since Nov. 2010 the EAHX is connected to a heat recovery ventilator (HRV), which operates only about 1 hour per day, when the owners comes back home. A thermometer measures the temperature difference between the outlet of the EAHX and the outside; it is found to average roughly 15 °C. Because of fears related to the development of moulds, the owner has not yet use the system during summer.

² <http://maisonleed.blogspot.com>

³ <http://www.ecohabitation.com/blog/52>

Seabird Island Sustainable Community Demonstration Project⁴

This project is located near Agassiz, BC. It includes a system of earth tubes providing ventilation air preheating. Each house has 92 m (302 ft) of underground 10 cm (4") diameter, un-perforated, "Big O" tubing. Whenever the upstairs thermostat calls for heat, the circulation fan forces air through a hot water coil and at the same time a ventilation fan draws air through the underground ventilation tubes. The house was monitored, results are available in CMHC (2009). The monitoring revealed that the earth tube system did not perform as expected. It showed problems with construction (leakage points where the tube comes out of the slab, resulting in minimum flow within the earth tubes themselves) and with the operation of the earth tubes, which were active mostly during cold period when infiltration through the building envelope is increased and additional ventilation air from the earth tubes is least needed. Because of concerns with their energy contribution and mould problems, the report recommended that the earth tubes be de-commissioned.

Systems designed by Chris Magwood

Chris Magwood has used earth tubes on two projects: the 4Cs Thrift Store in Haliburton⁵, and a private home. Both systems include a pair of 22.5 m (75 ft) long, 10 cm (4") tubes buried at least 5 ft deep.

The pipes come to the surface and are then pointed groundward by the use of two 90 fittings. A mesh and an insect screen cover the end. A rope was strung through the pipe as they were assembled, so that a sponge or other cleaning device could easily be pulled from one end to the other to clean the pipe.

At the 4Cs, the system is passive. Fresh air is only drawn into the building when there is a pressure imbalance between inside and out, typically caused by the exhaust fans in the building. No close monitoring of the system has been done, but the designer reports that it seems to have the desired result of warming air to ground temperature in winter and cooling it to ground temperature in summer.

At the private home, the intake from the earth tubes is brought to an HRV unit, so that the fan in the unit is pulling its fresh air supply from the tube and not directly from outdoors. The designer reports that this seems to work very well; he mentions that the earth tube eliminated HRV frosting problems that were happening at very cold outdoor temperatures.

⁴ <http://www.broadwayarchitects.com/sustainable-environmental-design-projects/seabird-island-sustainable-community.html>, <http://www.greenhomebuilding.com/seabirdisland.htm>, http://www.seabirdisland.ca/members/house_innovative.htm

⁵ <http://www.flemingc.on.ca/Alumni/FlemingTies/ties1205.pdf>

Prof. Tang Lee buildings

Prof. Tang Lee (University of Calgary) has worked on a number of systems (mostly commercial; see also Lee, 2004): a private residence in Millarville, AB (1986), a commercial greenhouse for Greenview Aqua-farm Ltd. in Conrich, AB (1988), a private residence in Crocus Ridge Estates, Calgary, AB (1988), the Dermatology Centre in Calgary, AB (1990), the Eco-House at the University of Alberta (2000), a sustainable duplex in Montgomery, AB (2001), the Seabird Island First Nations housing development, Agassiz, BC (2002), the Mayo Administration building, YT (2004), and the Cold Lake First Nation – Duplex, AB (2010).

None of these systems has been monitored as funding to establish monitoring programs could not be obtained. However Tang Lee reports that 10 to 15 °C increases in temperature in winter are common. A bypass is necessary in spring and fall, so is a differential thermostat. Generally a HRV is not connected to the EAHX since having an HRV and an EAHX in series is redundant⁶. Tang Lee mentions that there have been no obviously bad experiences with air quality; he recommends that air be kept moving constantly through the EAHX. He also recommends not placing the earth tubes next to a water line or sewer line as the earth tube may freeze the ground.

In terms of costs, Tang Lee specifies inexpensive plastic weeping tiles such as Big 'O', with a cost of about \$80-120/100 feet roll. A typical house requires 3 tubes. However, Lee reports that it is the cost of excavation that is more expensive. He mentions that it is possible to save on excavation costs if the same trench dug for utilities can be used for the EAHX (but not when there is water or sewage lines because of the potential for freezing). The systems use a dedicated fan as the fan in the typical forced air furnace is insufficient to overcome the pressure differential generated by air moving through the earth tube; however the fan/blower only needs to move air at 100-150cfm so it can be relatively small and inexpensive.

University of Alberta Ecohouse⁷

This project is located in Edmonton, AB. Ventilation of the EcoHouse is via an Earth Tubes system. Placed 6 feet underground, and stretching 100 feet between intake and entry into the house, three tubes bring in a constant supply of fresh air. Typical flow rate is 13.5 to 22.5 L/s (30-50 cfm) per 10 cm (4") diameter tube (total flow rate is 45 to 67.5 L/s (100-150 cfm)). The journey under the ground was designed to pre-cool the air in the summer, and pre-

⁶ More on this in section 4.3.

⁷ <http://www.uofaweb.ualberta.ca/ecohouse/index.cfm>

heat it in winter. The incoming air enters the return air ducts in the house, and because the furnace fan runs continually this provides a constant circulation of fresh air. The system was designed by Tang Lee at the Faculty of Environmental Design, University of Calgary, in October 2000. No performance information is available.

EcoPlusHome⁸

This house located in Bathurst, NB, has a heat recovery ventilator HRV₃₁ with earth collector 50 m (164 ft) around the house for passive cooling and heating, and a controlled room air exchange of 160m³/hr (5650 ft³/hr). The EAHX is made of 25 cm (10”) specialized corrugated pipe around the perimeter of the home. The pipe is a single piece with connections made only to the intake outside and to the intake of the HRV. All of the design calculations were done by Bosch by engineers in Germany; the pipes had to be flown in to Canada from Germany, but EcoPlusHome are currently qualifying Canadian companies that they will be using in future developments. The house is monitored but the EAHX itself is not, or at least not continuously.

Wilden Community⁹

The system for this house was designed by Trevor Butler at Archineers. It is located in North Kelowna. The system is monitored, with data accessible through the web¹⁰, but no aggregate analysis of the system performance (e.g. calculation of the Coefficient of Performance) was done. According to Trevor Butler, the Wilden House project is mostly for testing. It is not big enough to significantly displace the energy needs of the house, however it provides some limited pre-cooling or pre-heating. The system runs whenever the fan is running; the home is also cooled by natural convection. The house does not include a HRV; it does however have a 'conventional' water-source heat pump.

Trevor Butler has also included an EAHX in a system for Okanagan Lavender, for low-temperature drying of lavender; he has also designed half a dozen projects in the UK.

Maisons de A & A Construction¹¹

A & A Construction has developed a number of residences with EAHX. All but one are closed-loop systems (they are concerned only with temperature control, not bringing in fresh air). One of their recent applications was a wine cellar where the temperature is maintained at 16-18°C; cost of system was

⁸ <http://ecoplushome.com/>

⁹ <http://www.archineers.com/news/2009/12/10/earth-coupled-ventilation-live-data>

¹⁰ <http://www.welsolver.com/cgi-bin/show/WEL0148>, <http://welsolver.com/WEL0148/>

¹¹ http://www.ecohabitation.com/mon_entete/31

under \$500. Material generally used is 6" PVC. The systems function in two modes, summer and winter; in fall/early winter there is often no gain from the EAHX. They mention that one needs to use an electronically controlled motorized bypass as it is sometimes better to use outside air rather than air drawn through the EAHX. Generally speaking A & A designs houses with a high thermal mass; the ventilation system is not on during the day, but only at night. None of the systems has been monitored so far.

In a most recent project they abandoned the idea of using an EAHX in favour of a water-based loop with a cooling coil that will be integrated with the cooling system.

Maison d'Emmanuel Cosgrove¹²

This Montreal residence is described in the Better Buildings Case Study No. 63 published by CMHC (2009), and in *La Maison du 21ème siècle* (Vol 15, No. 3, p. 60-64). Originally built in 1907, the house underwent a significant renovation in 2006 that brought it to the LEED standard. It features an EAHX which is used only for air pre-heating; the system is not used for pre-cooling because the system does not include equipment to pump out condensates. Emmanuel Cosgrove mentions that he uses EAHXs in new buildings because the excavating work is already done; furthermore when there is already a HRV pumping the air through the EAHX, only incremental work is required from the ventilator. Emmanuel Cosgrove also notes that if pre-fabricated systems are used, the economics are not favourable because these systems are very expensive.

SynAIRgis house, Montreal

This residential system is located near Montreal. It serves a single family dwelling located in a rural environment. The purpose of the system is mostly air cooling. The aim is to be able to dispense with an air-conditioning system. The system will also be used during winter for pre-heating. Expected date of commissioning is Spring 2011.

The system was designed by SynAIRgis using polyethylene (PE) tubes with a smooth inside; a simple control algorithm is used and may be fine-tuned after the system has been running for some time. Monitoring of the system is planned.

Diane Schon and Masten Brolsma residence¹³

This house located in Calgary includes an earth tube system designed by Tang Lee. No additional information or performance data is available.

¹² <http://www.cmhc-schl.gc.ca/en/inpr/bude/himu/bebu/upload/66341.pdf>

¹³ <http://climatechangecentral.com/node/73>

Yanni Milon's residence, Shefford, QC.

This ecohouse was designed and built by Yanni Milon and Emmanuel Cosgrove. It is described in *La Maison du 21ème siècle* (Vol. 13, No. 1, pp. 8-10). It includes a 15 cm (6") EAHX made of corrugated PE. A 65 W fan is used to move the air through the tube. Performance data are not available.

Malagash House, Malagash, NS

This is a very low energy house in Northern Nova Scotia, designed by CoolEarth architects (Toronto). It features a 61 m (200') long Rehau EAHX with a 200 mm diameter. The architect was originally planning on using their own EAHX design, then switched to a Rehau system because of the antimicrobial coating of their tubes. The EAHX is connected to a Zehnder ComfoAir 550 HRV. The earth tube is designed to provide cooling as well as pre-heating. It is not clear how much cooling is required under current climatic conditions, but according to the architect there is a real possibility that because of climate change, some cooling may be required in summer in the future. The EAHX has been designed to provide all the cooling capability, there is no mechanical cooling system whatsoever. The house is expected to be completed sometime in 2011.

Rammed earth house in Hudson, QC

This house is described in *La Maison du 21ème siècle* (Vol. 15, No. 3, pp. 52-54). It features a 61 m (200') earth tube connected to an HRV. Performance data are not available.

Kevin Lepape residence¹⁴

This system, supplied by Rehau, equips a residence near Nelson, BC. It is about 220 ft long; the pipe runs in a vertical S behind a retaining wall because it could not be installed in the rocky terrain. The system is used both for winter and summer.

In winter, it runs in conjunction with a Venmar HE2.6 HRV. The HRV has two fans, therefore no additional fan was added for the EAHX. The HRV is used normally on low speed; it runs continuously except at night because of noise issues.

In summer, an auxiliary 200 W in-line fan is used to bypass the HRV. The fan is on a timer from 8 am to 8 pm. At night, the house is cooled down by natural convection.

¹⁴ http://na.rehau.com/files/LePape_vs2.pdf

Experience with the system has been positive. In winter, it is reported that the temperature of the air delivered started at 14-15 °C with outside air in the range 0 to 10 °C. The temperature went down through the winter, with the temperature of the air delivered going down to 8°C with outside temperatures in the range -25 to -8 °C. In summer, the hottest the house got was 22 °C with 32 °C outside (one cannot say for sure how much of this cooling effect is due to the EAHX and how much is attributable to other passive techniques such as overhangs; however when the EAHX is running the indoor temperature stays at 22 °C from morning to evening). In terms of economics, the savings were estimated (by the manufacturer, Rehau) at \$500 for heating per year (heating costs are around \$2,200 a year, as estimated from electricity bills); cost of the system was \$1,800 for the pipe, \$1,200 for the stainless steel air intake, and \$1,100 for shipping, for a total cost slightly above \$4,000. Excavation costs were minimal because the system was installed behind a retaining wall being built anyway.

Non-traditional residential systems

These systems are listed separately because they are built differently than traditional EAHXs.

Regina Healthy House Demonstration Project¹⁵

This project is located in Regina, SK. The earth tubes system is very unconventional with 30 m (100') of 10 cm (4") non-perforated intake duct inside 15 cm (6") perforated exhaust duct, buried in two feet of gravel under the suspended floor slab. The tubes are corrugated PVC. In-line fans in both the intake and exhaust lines control the flow of air. The outdoor end of the tubes are separated in a box at the west end of the house, located a couple of feet above ground. The house has a very tight envelope, and it does not feature a HRV (because of the way it is built, the system itself acts as a heat exchanger between intake and exhaust). Full monitoring was installed in Spring 2006¹⁶, with one year of monitoring planned. White (2007)¹⁷ presents one month of monitoring for January 2007, with outdoor air temperatures between -26 and +3 °C, exhaust air typically between 24 and 26 °C and inlet air at a temperature typically 2.3° lower than exhaust air¹⁸. It is not clear how much of the air tempering is due to conditioning by the earth and how much is simply due to heat exchange between intake and exhaust tubes. White (pers. comm.) points out that the temperature differential is almost independent of

¹⁵ <http://www.regina.ca/AssetFactory.aspx?did=609>

¹⁶ White T (2006) The Regina Healthy Housing Demonstration Project. Presentation by Terry White, Saskatchewan Office of Energy Conservation, April 28, 2006.

¹⁷ Same as White (2006), but updated and shortened.

¹⁸ It is not known whether the temperatures are measured before or after the fans.

external temperature, and that sometimes the inlet temperature is higher than indoor temperature because of radiant heat heating the inlet pipe. The system is used year round. Air quality is not a concern but is not monitored. There is no low point to collect and evacuate condensate in the intake; this was not viewed as a problem by the designer who considers the air to be usually dry¹⁹.

Vic Ellis projects

Vic Ellis (SCI Sustainable Concepts Inc., Pilot Butte, SK) has built around 50 systems - mostly residential, but also for a few churches. The systems are used only for heating. Vic Ellis reports that "they work well" although they are not continuously monitored. Temperature of the air entering the building is at least 4.4 °C (40 °F). No controls are used, and the systems are never bypassed.

Flowrate is typically 45 to 67.5 L/s (100 cfm to 200 cfm) for a house. The systems developed by Vic Ellis are not traditional EAHXs in the sense that they include 2 tubes side by side in ground: one exhaust line (perforated), and one intake line (non-perforated), typically 23 to 30 m long (75 to 100'); so in effect the system is as much a HRV as it is an EAHX. Ellis reports that no air quality problems have been experienced as long as air is running²⁰. The systems include a screen and a furnace-type filter.

Commercial systems

Government House²¹, First Nation of Na-Cho Nyäk Dun

This building near the village of Mayo, YT, designed by Broadway Architects (Vancouver, BC) includes underground ventilation shafts (Earth Tubes) that will pre-heat/cool air being drawn in for ventilation.

Marble Inn, Corner Brook, NL

This set of buildings apparently feature a 20 cm (8") EAHX system from Rehau, but no further details could be obtained.

Mountain Equipment Coop, Montreal

This building is mentioned in *La Maison du 21ème siècle*, Vol. 10, No. 2, p. 22.

¹⁹ This assertion should be taken with caution. In a basement dehumidifier study done by CMHC, people were surprised by how much moisture was being extracted from so called dry air. Thinking the air is dry does not mean there won't be condensation issues.

²⁰ The use of perforated tubes presents a risk of infiltration by radon gas if for some reason the fan stops.

²¹ <http://www.broadwayarchitects.com/sustainable-environmental-design-projects/government-house-butterfly.html>

Kortright Centre for Conservation²², Earth Rangers Centre

The centre features a very large earth tube system²³.

Enermodal Engineering building²⁴

This LEED Platinum building in Kitchener, ON includes a very short earth tube. System has not been monitored.

Electronic Arts (Canada) Inc.²⁵

This system located in Burnaby, BC, features an EAHX that tempers the outside air (warms it in winter and cools it in summer) before being fed into the air handling units. There have been no problems with this system; energy savings are unknown as the system is not monitored. The owner mentions that the only downside is the need to clean the intake grille yearly; access is considered a “confined space” and therefore needs some paperwork and monitoring by a second person.

David Suzuki Public School²⁶

This school under construction in London, ON, will feature a Rehau EAHX. Some monitoring is planned.

Craik Ecovillage, Craik Sustainable Living Project (CSLP)²⁷

The CSLP Eco-Centre in Craik, SK, is a multi-purpose community facility featuring innovative and energy efficient building design and integrated heating, cooling, and electrical systems. It includes an earth tube system. As stated on the website, "In summer air is drawn underground through five buried tubes and is cooled prior to being distributed throughout the building. In winter, cold outside air is drawn through the earth tubes where it is warmed by several degrees and is further heated by a radiator prior to being distributed". According to the operator, the system seems to work well. However, no monitoring has been done past the first week so this assertion is hard to verify.

New building at the University of Calgary

²² http://www.theaftend.com/designer/AFT_ER_annualreport.pdf

²³ <http://earthrangers.org/en-us/aboutus/building/ventilation.aspx>

²⁴

<http://www.cagbc.org/database/rte/582%20GRANDER%20VIEW%20PRESENTATION%20%28%29%20%5BR ead-Only%5D.pdf>

²⁵ <http://www.cagbc.org/uploads/EA%20Ph2%20LEED%20Certified%20Project%20Information%20.pdf>

²⁶ <http://www.gecdsb.on.ca/Schools/newSchools/suzuki/index.htm>

²⁷ http://www.craiecovillage.com/ecocentre_ecoconstruction.html

This will be a 1,800-3,600 m² (20-40000 ft²) building at the University of Calgary. It will include earth tubes (large enough to walk through) serving the auditorium. The purpose is heating and air conditioning, but the system is expected to be really beneficial in terms of cooling capacity because the University's cooling system is near its limit. The system will start in a few months. Monitoring is planned, with temperature probes located in the soil around the earth tubes to look for long-term thermal behaviour of the ground.

3.2 Earth tube systems in the USA

Klingenberg House²⁸ in Urbana, IL [*climate zone 5A*].

This house was built in 2003 according to PassivHaus guidelines. It includes a 30 m (100 ft) EAHX connected to a HRV. The HRV controller regulates ventilation air intake as follows²⁹:

- For an outdoor temperature of less than 13°C (55°F), ventilation air is drawn through the earth tube, where it is heated by the soil.
- For an outdoor temperature greater than 13°C (55°F), but less than the indoor air temperature, ventilation air is drawn through the conventional outdoor air intake grille.
- When the outdoor temperature equals the indoor air temperature, the heat recovery function is bypassed.
- For an outdoor temperature greater than the indoor air temperature, ventilation air is drawn through the earth tube, where it is cooled by the relatively cool soil.

The owner/designer, Katrin Klingenberg, mentions that EAHX are great in some climates (mostly not humid) and better for commercial buildings where they can be properly maintained. She also mentions the need for proper controls and, in addition to what is mentioned above, the need to always force at least 15% of the ventilation flow through the EAHX to avoid mould and air quality problems.

In EDU (May 2004)³⁰ Klingenberg notes that the EAHX in her house is of limited usefulness: "In some conditions, it starts warming the incoming air when it should be cooling it. Temperature changes occur not just between winter and summer, but also on a daily basis, so at night during the summer, the earth tube can warm the air when it should be cooling." For that reason the second PassivHaus house that was built did not include an EAHX.

²⁸ <http://www.thermotechwindows.com/EDU.pdf>; see also Stecher and Klingenberg, 2008.

²⁹ <http://www.nrc-cnrc.gc.ca/obj/irc/doc/pubs/b-1239.2/b1239.2.pdf>, p. 70

³⁰ http://www.passivehouse.us/passiveHouse/Articles_files/EDU%20May2007%20Postable.PDF

BioHaus at the Concordia Language village³¹

This residence in Bemidji, MN [climate zone 7], serves to house students attending language courses at the Concordia Language Village. It is built according to the PassivHaus standard and features a Rehau EAHX. The residence is 450 m² (5000 ft²) with two floors each 225 m² (2500 ft²). It houses 24 to 30 people in summer in a dormitory style housing, with a kitchen and a common room. It is used year-round, with most of occupancy in summer (June to August); the rest of the year is for weekend programs or week-long programs for adults.

The Earth tube system is used year-round, however it is shut down when the building is unoccupied (there is no mention that this causes any problem such as stale air when the system is restarted; some authors mention that air should be continuously moved to prevent the formation of moulds). Air from the earth tube also goes through an 85% efficient HRV. The system provides 100% fresh air. The speed of the HRV fan, which moves the air through the EAHX, can be continuously varied.

The system has been monitored since 2006. There are two data collection systems, one for the current week, one for long term data (some missing). Data collected include outside temperature (N. of building), ground temperature, temperature of air entering building, etc. Data is available only as graphs, and no performance summary could be obtained; to my knowledge no one is analyzing the data on a continuous basis.

3.3 Use of earth tubes in other countries

EAHXs have undergone extensive development in Europe and to some extent in Japan. The systems are more frequently seen there than they are on this continent, and there are numerous manufacturers who provide pre-designed systems for residential use³² (see section 7).

Some systems were installed as part of research projects and were monitored, such as the Darmstadt - Kranichstein Passive House³³ in Germany [climate zone 5A] or the BASF house³⁴ in Nottingham, UK [climate zone 5A]. Some manufacturers also present monitored data as part of their literature or on their web sites³⁵. However monitoring

³¹ <http://waldseebiohaus.typepad.com/>

³² See <http://www.fiabitat.com/realisations-puits-canadien.php> for a map showing installations done by one manufacturer.

³³ http://www.passivhaustagung.de/Kran/First_Passive_House_Kranichstein_en.html.

³⁴

http://www.energyefficiency.basf.com/ecp1/EnergyEfficiency/en_GB/portal/_/content/show_houses/show_houses_uk. Nottingham is in ASHRAE zone

³⁵ See for example: http://www.canada-clim.com/rubrique.php3?id_rubrique=6

is often only partly satisfactory and measured EAHX performance (in terms of energy gain, COP, etc.) is not easy to find for these projects.

Section 6 (Appendix A) provides additional references to residential and non-residential EAHXs which are described in scientific publications. Note that depending on where they are located, the EAHXs will have different purposes - pre-heating, pre-cooling, or both.

Emails were exchanged with various researchers involved with EAHXs in Germany, Switzerland and France to get an idea of the current evolution of research in that area. The following paragraphs summarize these discussions.

EAHXs have been used in some PassivHaus designs. However one researcher³⁶ notes that the technology is relatively expensive compared to its small energy savings, and that there are some concerns about humidity in the ducts. Usually the system would be dimensioned for frost protection of the heat exchanger. The Passive House Design Package³⁷ (PHPP) includes energy calculations for earth channels.

It is not clear if air quality with EAHXs has indeed been a problem with PassivHaus. An interview with Wolfgang Feist (Energy Design Update, 2008; see section 4.2.4) seems to indicate that problems have been experienced in some climates, and that EAHX are not considered for PassivHaus anymore.

Another German researcher³⁸ notes that EAHX have been widely used both for office and residential buildings. For commercial buildings, he notes that more and more buildings are using water-based systems with bore-hole heat exchangers, as they are more reliable at high summer temperatures and more independent from the outdoor air than EAHX. For residential buildings, standardized EAHXs are used mostly to avoid frosting of the HRV in winter and provide some cooling in summer. He notes the need to keep residential systems as simple as possible - in his view, this means no motorized bypass and no control system; manual systems (seasonal bypass, on/off switch) are preferable, with the system running continuously in winter and only a few hours during daytime in mid-season and summer.

A French researcher³⁹ notes that EAHX don't make sense when coupled to a HRV system since the EAHX tends to reduce the efficiency of the HRV. He adds that this is essentially useful for preventing the frost of the HRV unit, and that in France EAHXs are more relevant as a passive cooling solution in summer than as a pre-heating solution in winter.

³⁶ Juergen Schnieders, PassivHaus Institut, email dated 2010-12-09.

³⁷ http://www.passivhaustagung.de/Passive_House_E/PHPP.html

³⁸ Jens Pfafferott, Fraunhofer Institut, emails dated 2010-12-09 and 2010-12-13.

³⁹ Bruno Peuportier, ENSMP, email dated 2010-11-30.

The Swiss Minergie standard⁴⁰ was developed to promote sustainable, low-energy, comfortable buildings. To date there are about 20,000 certified Minergie buildings, most of them residential. According to one contact at Minergie⁴¹, 3/4 of these buildings feature an EAHX for preheating the air and protecting the HRV from frosting. According to the same source, there are no statistics about the various systems used nor about the estimated performance. The Minergie guide for the design of ventilation systems⁴² contains a section on EAHX.

3.4 Brine based systems

As mentioned already, an alternative to earth tubes is the use of a brine or glycol loop with a heat exchanger located at the entrance of the heat recovery unit. These systems feature a small diameter polyethylene (PE) pipe filled with anti-freeze (brine or glycol) buried a minimum of six feet underground in a trench. Heat is transferred to the incoming air stream through a liquid-to-air heat exchanger. Such systems solve some of the risks associated with EAHX (growth of moulds, infiltrations of radon); see for example Bean (2010) and Eicher (2010). As indicated in section 3.3 it is reported that they are apparently as efficient as air-based systems in heating mode, but less efficient in cooling mode (see Cahiers techniques du bâtiment, 2010). Canadian and US Passive House Institutes, which promote the PassivHaus standard in North America, indicate a move away from EAHX in favour of brine or glycol based loops:

[USA] "Earth tubes were used for the energetic gain, but more importantly for the purpose of a defrost option. Earth tubes can contribute significantly to pre-heating, pre-cooling and dehumidification. In the recent years, earth tubes have been more and more replaced by closed-loop ground heat exchange systems that involve only the energy input of a very small pump, eliminating concerns of condensation issues" ⁴³.

[Canada] "In the past 3 years liquid-based geothermal heat exchangers have largely replaced earth tubes in new Passive House construction, since they do not require ventilation air to be passed underground. In this case a suitable fluid (e.g. brine) is circulated at low velocity by a small pump in a 2.5 to 3.7 cm (1 or 1.5") poly pipe beneath slab insulation or in adjacent trenches, before passing across a heat exchanger located in the incoming ventilation air

⁴⁰ http://www.minergie.com/home_en.html

⁴¹ Thomas Kühne, Minergie, email dated 2010-12-15.

⁴² <http://www.batirbio.org/html/attachments/Ventilation/Lueftung.f.pdf>

⁴³

<http://www.passivehouse.us/bulletinBoard/viewtopic.php?f=5&t=208&start=0&st=0&sk=t&sd=a&sid=f1631d12f90c9e51150dc4120ee695d>

stream. Such systems can achieve high performance coefficients, and can eliminate the need for automatic defrosting of the HRV unit - often an expensive and frequent necessity in a Canadian winter climate" ⁴⁴.

Based on the literature search, the advantages of these systems have not been clearly demonstrated in North America, and their economic benefits are not known. Some of the open questions raised by EAHXs (see section 4.2) also concern brine or glycol-based systems: possible long-term temperature imbalances in the ground, reduced efficiency of the HRV when combined with a glycol loop, and need for controls.

4 Synthesis

4.1 Current accomplishments

The research completed for this project has shown that, from an energy use point of view, EAHXs can bring definite benefits in some climates. These benefits are observed on a seasonal basis (i.e. average temperatures vary less than ambient temperatures from one season to the next) but also on a daily basis (temperature during the day is relatively constant). Examples of measured data illustrating the temperature equalizing effects of EAHXs can be found for example in the graphs of Sections 9 and 11 in Fjaerem (2004); Figure 5 in Grosso & Raimondo, 2007; Figure 2 in Henkel et al., 2004; Hollmuller, 2003; Figures 18, 22 and 23 in Jautard and Trombe (2003); Figures 5, 6 and 7 in Pfafferott J (2003); and pp. 87-91 in Loyau (2009); additional examples can be found in Breesch et al. (2005) and in the Canada-Clim website⁴⁵. For the climates considered in the articles, EAHXs seem to be particularly effective in cooling applications. Their use during hot summer days has proven very effective in clipping temperature peaks: EAHXs provide chilling when it is needed the most, during the middle of day in summer, when temperature difference between ambient air and earth temperature is at its greatest

The contribution of EAHXs to pre-heating in winter, when a HRV is used, appears somewhat minimal. One of the touted advantages of connecting an EAHX to the HRV is to protect the unit from frost; however other options exist which are well adapted to the Canadian climate, such the use of a defrost cycle⁴⁶.

EAHXs have been deployed extensively in Europe, although by total numbers the market penetration is still relatively low. There are many design tools available, and

⁴⁴ <http://www.passivehouse.ca/design/ventilation>

⁴⁵ <http://www.canada-clim.com/>

⁴⁶ <http://oee.nrcan.gc.ca/publications/infosource/pub/hrv/operating.cfm?attr=4>

EAHX are integrated into several norms and low-energy design standards, such as VDI 4640 - Part 4, European Norm EN15241, PHPP, and Minergie.

4.2 Open questions

Nevertheless, many questions remain regarding the applicability of EAHXs to Canadian climatic conditions.

4.2.1 *Lack of monitored data*

Despite the number of residential EAHXs in service, particularly in PassivHaus and Minergie designs, there is a surprising lack of comprehensive data about the actual energy and IAQ performance of systems. Measurements that are available are often incomplete and insufficient (for example it is not always clear if reported temperature gains include heat released by the fan). Among published data, there is a very wide range in reported COPs and energy gains. This is due partly to the nature of the system. For example the COP and cooling or heating capacity of the EAHX varies with the temperature difference between ambient air and ground: therefore the capacity and COP will appear very high when the difference is greater, and very low when the temperatures are close to each other. The numbers will appear radically different depending on when they are measured or over what period they are averaged. Seasonal COPs are frequently reported in the range 3 to 4 with some authors reporting values as high as 35 to 50. A typical residential EAHX is reported to have an average cooling power around 1.5 kW with peak cooling power around 4 kW, although this will of course depend on local climatic and soil conditions.

Only a limited number of systems have been found installed in houses in North America. A few are manufactured, but most are custom-made. Users report mixed results. Some users express general satisfaction with the systems, but objective performance indicators are lacking. Other users report that their systems do not always work as expected. In short, it is hard to draw general conclusions from the current stock of systems installed in the USA or Canada.

Compounding this uncertainty are two effects which are often neglected or incompletely addressed: controls and long-term imbalances in the ground.

4.2.2 *Controls*

The literature reviewed strongly suggests that EAHXs should not be used 24/7, year round. There are indeed numerous reports of EAHXs delivering warm air when cold air is needed, or vice versa (Gustafsson 1993; Henkel et al., 2004; Hollmuller and Lachal, 2001; Wagner et al., 2000; Pfafferot, 2003; Janssen et al., 2006; EDU 2007).

For example in the middle of summer it may be beneficial to stop the EAHX at night and draw air directly from the outside because it is cooler. The problem is also prevalent in mid-season. The literature indicates that EAHX working under such adverse conditions provide a very significant 'negative' contribution to the overall heating or cooling needs of the building (see Wagner et al., 2000). Several solutions have been used, such as manual controls (seasonal bypass or manually operable switch), or automated bypasses. The latter should be considered seriously in any installation (Eicker et al., 2006, Henkel et al., 2004; Pfafferot, 2003; Santamouris, 2006).

4.2.3 Long-term temperature imbalance in ground

In the literature reviewed, long-term reduction in the heating/cooling capacity of the ground is often not properly considered. System performance is often measured immediately after the EAHX fan is turned on, but not after a week or two of operation. There is some evidence in the literature that the heating or cooling capacity of the soil becomes much diminished after some time (depending upon numerous factors such as thermal properties of the ground, flow rate in the EAHX, etc.), and that the heating or cooling capacity measured over a month will be much lower than that measured over one day (Argiriou et al 2004; Eicker 2010; Fjierem, 2010; Henkel et al., 2004, Lee, 2004; Santamouris, 2006). This effect is not sufficiently quantified. It happens both in winter and in summer - for example operating an EAHX in a very cold climate for weeks in winter with sub-zero temperatures may actually freeze the ground around some parts of the EAHX; and in summer, the EAHX may prove effective in the first few days of a heat wave but not if the heat wave persists.

4.2.4 Air quality

Based on the literature and interviews, air quality does not seem to be a problem, as long as the system is properly designed, installed, operated and maintained. A properly conceived system will have smooth tubes (possibly with anti-microbial coating), a sloping design collecting and evacuating condensates at a low point, tight joints, and proper filters at the air intake. Air will not be left stagnant in the tubes; the filters will be replaced regularly. Under such conditions, air of good quality can be delivered to the building, as documented in Flückiger et al. (1998, 1999) and Wagner et al. (2000). Note however that in these studies air quality is attributable more to the use of filters than to the use of a EAHX.

Nevertheless, the potential for condensation on the surface of the tubes in summer, where warm, humid air is drawn through tubes in contact with cool earth, is a concern to some, as it may be conducive to the growth of bacteria. In an interview with EDU (2008) Prof. Feist, the originator of the PassivHaus standard, reports air

quality problems (condensation, mould) with earth tubes in northern Europe, especially in Scandinavia, but not in Central Europe, although they aren't sure why. Similarly Staahl (2002) reports problems with systems in Sweden; Stecher and Klingenberg (2008) also mention odor problems. This area seems to be somewhat incompletely understood (see EDU, 2008) so caution should be exerted when considering such systems for Canada, specially since places where problems have been reported (Scandinavia) have climates very similar to some parts of Canada.

4.2.5 *Interaction with the rest of the building*

Some EAHX systems have been located around the foundations of the residence or under the basement floor slab, the idea being that the system can reclaim some of the heat losses of the house. From the literature reviewed It is not obvious that this approach is actually beneficial, because it actually exposes the slab or the foundation to colder air. In at least one example (Hollmuller, 2003) it has been shown to have a globally negative influence on the thermal balance of the building.

4.3 EAHX and HRV

Strictly from an energy point of view, the literature reviewed offers very strong evidence that combining an EAHX and a HRV provides little benefit in heating mode. In plain terms, they are both trying to eat the same piece of the pie. The situation is very well explained in pp. 54-55 of Loyau (2009) which inspired the following simplified example.

Consider a situation where the outside air temperature is -5°C , the indoor air temperature is $+21^{\circ}\text{C}$, and the effectiveness of the HRV is 80%.

In the absence of an EAHX, the HRV will recover 80% of the temperature difference ($\Delta T = 26^{\circ}\text{C}$) bringing the outside air to $-5 + 0.80 \times 26 = 15.8^{\circ}\text{C}$.

A good EAHX would raise the outside temperature typically by 13° and bring it to $+8^{\circ}\text{C}$. Then the HRV will recover 80% of the remaining temperature difference ($\Delta T = 21 - 8 = 13^{\circ}\text{C}$) bringing the outside air to $8 + 0.80 \times 13 = 18.4^{\circ}\text{C}$.

The 'actual' contribution of the EAHX is therefore just 2.6°C , which is small (assuming a ventilation rate of 45 L/s (100 cfm) this corresponds roughly to 140 W). The same effect could be obtained by using a higher efficiency HRV.

When an HRV is present, the advantage of combining it with an EAHX is therefore minimal from an energy point of view. This is confirmed by studies such as Hollmuller and Lachal (2001); Janssens et al. (2006); Pfafferot (2003); Tittlein et al. (2009);

Wagner et al. (2000); VDI (2004); Herzog (2010); and Loyau (2009). The benefit of the EAHX is to provide frost protection to the HRV, although other methods can achieve the same result at a lower cost. Several papers have shown that when an EAHX and a HRV are in series, the EAHX's energy contribution is only 10 to 25% that of the HRV (Janssens et al., 2006; Wagner et al., 2000; Herzog, 2010).

4.4 Economics

With earth tube system costs typically in the range \$2,000 to \$3,000, payback is often long given the expected energy savings. One manufacturer mentions between 10 and 20 years as long as excavation costs are kept to a minimum. Fjaerem (2004) mentions a €7,500 cost and a 9-year payback. Stecher and Klingenberg (2008) report that the earth tube is not cost effective. Various people interviewed during this study have mentioned that excavation expenses are one of the big drivers of the overall cost of the system. Other factors which reduce the economic appeal of EAHX include the fact that the systems tend to work seasonally, that they require sophisticated controls or risk heating and cooling when they should not, and that they overlap the functionality of the HRV (if supplied) in heating and cooling modes.

There may be other non-monetary advantages to EAHX, such as the possibility to obtain LEED points.

4.5 Applicability of EAHX

One clear result of this study is that there is no 'one size fits all' approach to the use of EAHXs. First, these systems should only be used with tight envelopes: when infiltration is high, the earth tubes provide additional fresh air that is not needed (see CMHC, 2009). Generally speaking, the availability of large daily outdoor air temperature swings seem also conducive to the use of EAHX. On the other hand, mild temperatures usually result in low COPs. In cooling applications, EAHXs do not seem to have significant dehumidification potential (Stecher and Klingenberg, 2008), a capability that is required for a number of Canadian locations.

Other than those general rules, a case-by-base approach is needed. One cannot provide 'universal' guidelines as to the potential for heating, cooling or both: this is really dependent upon the location, the type of building, the properties of the soil, the presence of a HRV, etc.

EAHXs are very subtle systems which require careful design and operation to be successful. The literature has many examples of systems with problems (see CMHC 2009; EDU 2009; IEA Annex 28, 2001) - systems that don't work as expected, or systems with poor air quality, etc. leading to disenchantment with the system and in

many cases decommissioning as it is often very difficult to fix EAHXs once the trenches are back-filled.

Design manuals such as those mentioned in section 6.2 are available to guide the design and construction of an EAHX. Other good introductory readings on the design and construction of EAHXs are Bean (2010), Haghighat (2004), Santamouris M (2006), IEA Annex 28 (2001), CTB (2010), CETIAT (2008), books by Loyau (2009) and Herzog (2010), and web sites such as www.fiabiat.com/puits-canadien.php or www.batirbio.org. The reader should be warned, though, that some of these publications refer to applications in Europe for climates that differ significantly from Canadian conditions, or concern commercial systems rather than residential ones.

Each case should be evaluated with a well-calibrated simulation program. Note that the simulation should not simulate the EAHX in isolation, it should also take into account other related systems and the rest of the house. For example, as seen above, estimating EAHX gains without considering the presence of a HRV in series would be misleading. Similarly the ventilation needs of the house, their control, and the possible use of natural cooling, will all have consequences on the performance of the EAHX. Finally, long-term thermal imbalances have to be taken into account by the model.

Manufactured systems have been designed to address many of the challenges posed by earth tubes, and therefore may offer an improved approach to consumers and industry in terms of material, condensation, noise, controls, etc. Proper calculation, simulation, etc., which are often provided by companies specializing in EAHXs, are also pre-requisite to any installation.

5 Conclusion

This study has shown that research seems to show that EAHX may have benefits when used under the right conditions and in the right climate, but also that they are very subtle systems which require careful design and operation to be successful. An improperly designed system will not work as expected, or result in poor air quality, etc. leading to disenchantment with the system and in many cases decommissioning: it is often very difficult to fix EAHXs once the trenches are back-filled.

Controls, air quality, and thermal memory of the ground are but three of the areas to be concerned about when considering whether an EAHX is worth it. One also needs to be conscious of the redundancy with the HRV, and be aware that the economics are rarely favourable.

One clear result of the present study is that there is no 'one size fits all' approach to the use of EAHXs. Each design will be a particular case based on local climatic conditions, soil properties, and house characteristics. There exist many books, manuals, papers, and web sites, which can be helpful in researching and designing the system. One should avoid building one's own system from scratch, as doing so more often than not results in problems (manufactured systems, on the other hand, avoid some of the many pitfalls that can plague poor designs).

The use of a well-calibrated simulation program may help in assessing each particular case. Note that the simulation should not simulate the EAHX in isolation; it should also take into account the rest of the house. For example estimating EAHX gains without considering the presence of a HRV in series would be misleading. Similarly the ventilation needs of the house, the controls considered for the EAHX, and the possible use of natural cooling, will all have consequences on the usefulness of the EAHX.

The performance of EAHX in most of Canada's climatic conditions has not yet been demonstrated through validated rigorous energy and indoor air quality monitoring. Until such data can be obtained, the findings from this project need to be carefully evaluated prior to undertaking any such installation.

6 Appendix A: Annotated bibliographic summary

6.1 Scientific papers and publications

Argiriou A, Lykoudis S, Balaras C and Asimakopoulos D (2004) Experimental study of a earth-to-air heat exchanger coupled to a photovoltaic system. Trans ASME, 128, 620-625.

Residential system, Athens, Greece [climate zone 3B; no equivalent in Canada].

The authors study a system coupling an earth-to-air heat exchanger with a photovoltaic system, to make use of the good match between cooling needs and availability of solar radiation (used to generate photovoltaic electricity to power the fan). Measured average temperature drop between inlet and outlet of the heat exchanger ranges from 1.4°C in September to 4.7°C in June, during which it can reach values as high as 9.8°C. The authors observe that the system performance is maintained throughout the season, despite the fact that ground temperature increases by about 10°C in the vicinity of the tubes during that period. The authors also report a COP of 12 for the system.

Bean R (2010) Down to Earth - and 'exhumation' of Earth Tube Heat Exchangers. Downloadable from http://www.hpacmag.mercuryemail.com/archives/2010/March/1_Complete%20Issue.pdf

A good, two-page summary about the benefits and pitfalls of earth tubes. mentions gains of 10 to 20°C in temperature with COPs of 3.3 in cooling and 3.8 in heating. Also mentions the possible use of glycol loops to circumvent some of the problems of EAHXs.

Boithias F, Zhang J, El Mankibi M, Haghighat F and Michel P (2009) Simple model and control strategy of earth to air heat exchangers. ACTEA 2009, July 15-17, Zouk Mosbeh, Lebanon.

Simulation paper.

This is a simulation paper which proposes some simple but interesting algorithms for controlling EAHXs.

Breesch H, Bossaer A and Janssens A (2005) Passive cooling in a low-energy office building. Solar Energy 79, 682-696.

Commercial system, Kortrijk (Belgium) [climate zone 5A].

The paper describes monitored data for a relatively small office building (three levels each 500 m²) equipped with a large EAHX (2 tubes each 40 m long, diameter 80 cm). The building makes also use of night-time cooling. Temperature of the air coming from the EAHX never exceeded 22°C, leading to an important cooling effect on hot summer days. When maximum ambient temperature falls between 12 and 22°C the cooling effect is limited, and a heating effect is observed when the maximum ambient temperature is below 12°C. Summer thermal comfort in the building was good, but the authors show with the help of simulations that the EAHX has a limited contribution compared to natural cooling.

Burton (2004) - see full reference under Fjaerem (2004).

Cahiers techniques du bâtiment, No. 300 (Octobre 2010) Faire bénéficier l'air neuf de l'inertie thermique de la terre.

Summary paper.

This article presents an introduction to EAHXs. It reviews design, installation and control issues. Noted advantages are tempering of the air in summer and pre-heating in winter. The EAHX also eases the load of the air heating and conditioning system during extreme temperatures, which enables to limit equipment over-sizing. The article also mentions the use of glycol-based water loops, and indicates that their heating potential is equivalent to that of air-based EAHXs but their cooling potential is lower.

CMHC (Feb. 2009) Technical Series 09-101. Downloadable from <https://www03.cmhc-schl.gc.ca/catalog/productDetail.cfm?cat=151&itm=3&lang=en&fr=1291990917989>

Residential system, Agassiz, BC.

This short Research Highlights gives an overview of monitoring results for the Seabird Island demonstration project. This project was "designed and

constructed to promote and demonstrate sustainable approaches for the design and construction of First Nation housing". The project was located near Agassiz, BC and included seven units with earth tubes systems. The study concluded that the earth tube system did not perform as expected. This may be due partly to problems with construction (leakage points where the tube come out of the slab, resulting in minimum flow during the earth tubes themselves) but also to the operation of the earth tubes, which were active mostly during cold periods when infiltration through the building envelope is increased and additional ventilation air from the earth tubes is least needed. This Research Highlights condenses a report to CMHC by Ken Cooper, SAR Engineering Ltd. (2006). This reports contains additional information, such as mould tests which may suggest mould amplification in the earth tubes, possibly because of exposed soil, however the results are fairly inconclusive. Because of concerns with their energy contribution and mould problems, the report recommended that the earth tubes be de-commissioned.

Cooper K (2006) Seabird Island Monitoring Report. See full reference under CHMC (2009).

EDU - see full reference under Energy Design Update.

Eicker U (2010) Cooling strategies, summer comfort and energy performance of a rehabilitated passive standard office building. Applied Energy 87, 2031-2039.

Commercial system, Tübingen, Germany [climate zone 5A].

Part of this paper deals with the performance of a EAHX installed in a rehabilitated small (833 m²), two-storey office building. It features a 72% efficient HRV and a brine-based ground coupled heat exchanger installed around the building perimeter; total length is 500 m. The building has been monitored extensively for over two years. The COP has a maximum value of 40 with an average value of 18.4. Maximum heat dissipation per meter of tube is 8 W; maximum measured cooling power was measured at 4 kW with an average of 1.5 kW measured during a 14-day period in June; however the contribution of the system to the overall cooling load of the building is deemed minimal. The paper also notices that when the EAHX was operated for two months during the summer, the daily mean earth temperature increased by 2-3°C compared to the undisturbed soil at the same depth; this clearly indicates thermal loading of the soil.

Eicker U, Huber M, Seeberger P and Voschulze C (2006) Limits and potentials of office building climatisation with ambient air. Energy and Buildings 38, 574-581.

Commercial system, Weilheim, Germany [climate zone 5A].

A three-storey, 1,500 m² passive office building was monitored for over three years. The building features 180 m of heat exchanger circling around the building at a depth of 2 m. The paper provides details about the control

algorithm of the building: in heating mode, the EAHX is bypassed if soil temperature is colder than air temperature; in cooling mode, it is bypassed if room temperature is below 22 °C. The paper notices that unwanted gains can still occur when outside temperatures are lower than soil temperature in summer; a better control strategy should take into account inlet air and soil temperature. Average COP (for heating and cooling combined) is estimated at 50, 35 and 38 over the three years. However the EAHX covers only about 20% of the building's cooling load, for a large part because of high internal gains.

Energy Design Update (May 2004), Vol 4, no 5. An Illinois “Passivhaus”.

Residential system, Urbana, IL [climate zone 5A].

This paper provides details of the PassivHaus built by architect Katrin Klingenberg, including its 8” (20 cm) diameter, 100 ft (30 m) long EAHX. The house includes an HRV with control dampers that select between two possible air intake ducts depending on outdoor temperature: in cold weather outdoor air is drawn through the tubes (for pre-heating), in intermediate weather it is drawn directly from outside, in very warm weather it is drawn again through the tubes (for pre-cooling)⁴⁷.

Energy Design Update (May 2007) Vol 27, no 5. Urbana gets another Passivhaus.

Residential system, Urbana, IL [climate zone 5A].

The description of the second Passivhaus in Illinois reflects on experience from the first house (see EDU, May 2004), in particular with respect to the EAHX. Contrary to the first house, the second house has no buried earth tube. ‘We have evaluated the effectiveness of the earth tube [at the first house] ... it was only of limited usefulness. In some conditions it starts warming the incoming air when it should be cooling it. Temperature changes occur not just between winter and summer, but also on a daily basis, so at night during the summer the earth tube can warm the air when it should be cooling’. ‘I was at the Pasivhaus conference in Germany, and it seemed that a lot of people in Europe are moving away from the earth tubes ... they’re not sure they are really doing what they are supposed to’.

Energy Design Update (Jan. 2008) vol 28, no 1. Downloadable from

http://www.passivehouse.us/passiveHouse/Articles_files/EDU%20Jan%2008.PDF

Summary paper.

This article contains an interview with Wolfgang Feist, founder of the PassivHaus Institut in Germany. He reports air quality problems with earth tubes in northern Europe, especially in Scandinavia, but not in Central Europe, although they can't figure why. He also mentions that EAHXs are not advertised for passive houses anymore, mainly because they are too expensive and because they are redundant when a HRV is used.

⁴⁷ The strategy is only partially successful; see EDU (2007).

Energy Design Update (Feb. 2009) Vol. 29, No 2.

Residential system, Vermont.

A good example of site-built earth tube system that doesn't work, in part because of excessive noise, and in part because of drainage holes that let water in when the water table rises.

Fjaerem A (2004) Coolhouse - Final monitoring report. Downloadable from <http://www.softech-team.it/Coolweb/CoolHouse-Monitoring-PT.pdf>

See also overall report for project: Burton S (2004) Coolhouse - Final Technical Report. January 2000– December 2003. Energie Demonstration Project NNE5 –1999 - 193. Downloadable from <http://www.softech-team.it/Coolweb/CoolHouse-FinalReport.pdf>

Residential systems, Alma Verde, Southern Portugal [climate zone 3C; no equivalent in Canada].

This report summarises monitoring results for three houses that incorporate several advanced features including earth tubes. The tubes run only for part of the day (typically mid-afternoon to early morning). The system was monitored. There were several factors that made the monitoring effort somewhat inconclusive: it was conducted for only 6 months (mid-July to mid-January); the soil around the earth tubes had been recently disturbed and its temperature did not have the time to settle. Nevertheless the study showed that the earth tube is excellent at removing the peaks and troughs of daily outdoor temperature. Maximum temperature differential ΔT was -11°C in cooling and $+8^{\circ}\text{C}$ in heating. Cooling power depends strongly on the ΔT and is evaluated at roughly 4.8 kW on average. Average cooling was originally estimated around 2.5 kW.

The idea to run the EAHX from the middle of the day throughout the afternoon and until the early hours of the following morning was to thermally recharge the ground. The report says that this may not be necessary, although it does not provide evidence for it. The report does mention, however, decreasing effectiveness at removing heat when several hot days occur in a row, as heat builds up within the ground, causing a reduction in the efficiency of the EAHX.

Flückiger B and Monn C (1999) Microbial investigations and allergen measurements in ground-coupled earth-to-air heat exchangers. Proc. Indoor Air 99, Edinburgh, Scotland, 8-13 August 1999, Volume 5, pp 13-18.

Air quality paper.

This paper contains much of the same material as Flückiger et al. (1998) but also provides a longitudinal study of spores which shows a general decrease along the way of the air stream. This is explained by sedimentation and impaction of the spores on the bottom and on the walls of the tubes.

Flückiger B, Monn C, Lüthy P, and Wanner HU (1998) Hygienic aspects of ground-coupled air systems. *Indoor Air* 1998, 197-202.

Air quality paper.

In this very thorough study the authors investigated air quality for 12 EAHX, both in commercial buildings and in dwellings; some of the systems had been in operation for several years. They found that the concentrations of fungal spores and bacteria in the air at the end of the EAHX were generally lower than in the outdoor air, and more so for large commercial EAHXs than for residential ones. However a small increase in bacterial count was observed in two residential systems. High flow rates seemed to be beneficial.

Concentration in the supply air was always low, thanks to removal of bioaerosols by filters. They concluded that the systems are safe to operate; they recommend the use of a coarse filter at the inlet of the EAHX to prevent ingestion of dusts and bioaerosols, proper design of the system (smooth inner surface, slope) to prevent water accumulation, and proper maintenance including occasional cleaning of the inside of the EAHX.

Grosso M and Raimondo L (2007) Horizontal air-to-earth heat exchangers in Northern Italy: testing and application. 2nd PALENC Conference and 28th AIVC Conference on Building Low Energy Cooling and Advanced Ventilation Technologies in the 21st Century, September 2007, Crete Island, Greece.

Residential system, near Turin, Italy [climate zone 4A]

The application is a 48 m long EAHX in a single family house. The system monitoring was only partly successful because of equipment failure and only 3 months of monitoring are available. Different modes of ventilation were tested (no ventilation, low and high flowrates 24h/day, and high flowrate from 8:00 to 20:00). The paper provides a graph with daily values of COP which range approximately from 1 to 8. Maximum daily average cooling power ranges from 1 to 2 kW and daily cooling energy is frequently in the range 15 to 25 kWh. The paper also mentions that the intermittent operation of the EAHX is beneficial to recharge the cooling potential of the ground, but that continuous operation achieves the same result when ambient temperature drops below soil temperature at night.

Gustafsson SI (1993) Are earth tube heat exchangers of interest when heating buildings? *Int. J. Energy Research* 17, 597-604.

Unspecified kind of system near Linköping, Sweden [climate zone 6A]

The paper reviews measurements from two EAHXs used for heating (it does not specify the kind of building which they served). It mentions that the results were overall discouraging, mostly for control reasons as the earth tube sometimes cools the air instead of warming it. Heat transfer was evaluated around 100 W/m.

Haghighat F (Ed.) (2004) Chapter 4 - Earth to Air heat exchanger and earth coupling. In Perino (Ed.) (2004) Annex 44 report - State of the Art review - Vol 2A. - Responsive Building Elements. International Energy Agency, Energy Conservation in Buildings and Community Systems Programme.

Commercial buildings

This chapter focuses mostly on large systems for commercial buildings, for which it provides some monitored data. The paper is mostly interesting in its summary of benefits and limitations of EAHX. The authors note that EAHXs have been used with good success for many buildings, and they suggest that buildings with the following factors are potential users of EAHXs (for cooling): moderate cooling loads, low ground temperature, large daily outdoor air temperature swings, relatively low requirements for indoor environment, and use of a displacement ventilation system. They also list barriers to application, including possibility of noise created or transmitted by EAHXs, risks of contamination, lack of confidence of building owners in the technology, systems costs, and difficulty of installation (slope of system, leak tightness). They list as open questions the optimization of control strategies, the balance between heating and cooling, both diurnal and seasonal, the long-term capability of the soil, and whole building integration and optimization.

Henkel J, Chen B, Liu M and Wang G (2004) Analysis, design and testing of an earth contact cooling tube for fresh air conditioning. Proc. Solar 2004, July 11-14, 2004, Portland, OR.

Residential system, near Omaha, NE [climate zone 5A].

The paper presents monitoring results for a 57-m EAHX used for cooling of residential buildings. The design is somewhat questionable as holes are drilled into the bottom of the tube over its entire length to enable moisture to trickle out – a feature that exposes the system to radon gases and to infiltrations. Nevertheless, tests performed during the summer with continuous flow rates of 1,320 and 1,680 m³/h show a cooling potential up to 3.8 to 5 kW. The cooling potential varies with air temperature during the day. The paper also notices warming of the air if the ambient temperature drops below the temperature inside the cooling tube. The paper points out that realistic use conditions would allow the system to be shut down during the night and let the soil recharge thermally. The COP is estimated at 4. Increases in ground temperature are observed, although it has a minor effect on the capacity of the system.

Hollmuller P (2003) Potentiel de rafraîchissement par « géothermie proche » : puits canadiens et techniques apparentées. Workshop « Geo-cooling », Neuchâtel, 16 oct. 2003. Downloadable from http://www.solarenergy-thermal.ch/rapports/Siteo/fr/RA2003_Potentiel_Rafraichissement_Puits_Canadien_Hollmuller.pdf

Summary paper

This document includes several examples of EAHX or similar (for example taking cool air from the basement to condition the attic). It puts in clear context the two possible functions of EAHXs, namely the seasonal dampening and the daily dampening of temperature variations. It also presents an interesting example of a system with a glycol loop located under the building, which results in a global loss of energy because the earth heat exchanger amplifies diffusive thermal losses from the building.

Hollmuller P and Lachal B (2001) Cooling and preheating with buried pipe systems: monitoring simulation and economic aspects. *Energy and Buildings* 33, 509-518.

Commercial systems, near Zürich [climate zone 5A] and Geneva [climate zone 4A], Switzerland.

The paper presents a numerical model as well monitored data for a greenhouse and a 2900 m² multifamily/commercial building. In heating mode the EAHX is coupled with a 60% efficient HRV. Calibrated simulations show that the EAHX contributes 27.1 MWh per year, vs. 31.9 MWh for the HRV. However if the heat exchanger were to be used alone, it would still recover 49.6 MWh, so the actual contribution of the EAHX is $(27.1 + 31.9 - 49.6) = 9.4$ MWh, which is low; an increase in the efficiency of the HRV could easily provide similar gains. The authors conclude that implementing both an EAHX and a HRV in series does not make economic sense. Cooling potential is estimated at 19.6 MWh. The authors note that the air is globally heated up by the EAHX during the summer; they claim it is acceptable because the purpose of the EAHX is to keep the air below 26°C by smoothing ambient temperatures over 24 h or a few days. Higher flow rates enable to provide more cooling. The authors suggest that the economic interest of the system lies in cooling, where the use of an EAHX may enable to dispense with a dedicated air-conditioning system; heating in itself is not economically interesting but it becomes an additional free service when a system is installed for cooling purposes.

IEA Annex 28 (2001) Low Energy Cooling: Technology selection and early design guidance, Chapter F – Ground Coupled Systems.

Summary paper

The focus of this document is obviously cooling, but some of the information presented in the document is also applicable to heating. The chapter has It includes information about EAHX positioning, size, and operation; it provides charts and tables for system sizing, practical guidance for air intake, distribution and collection ducts, the ground coupling piping system, and maintenance.

Janssens A, Steeman M, Desmedt J, Hoes H and De Paepe M (2006) Energy performance of earth-air heat exchanger in a Belgian office building. Proceedings of the 2005 AIVC Conference. Downloadable from

http://www.vito.be/VITO/EN/HomepageAdmin/Home/WetenschappelijkOnderzoek/p_catalogus.htm

Office buildings in Kortrijk, Belgium [climate zone 4A].

The paper reviews the performance of an EAHX in a low energy office building⁴⁸. The EAHX is coupled with a regenerative heat exchanger (RHX). The system is designed to pre-cool the air for the building. It was found that night cooling is more efficient than EAXH to improve thermal comfort. The EAHX is good for peak heat removal (25 kW) but “in milder weather the EAHX may have an adverse effect: it still cools the air during part of the time when the building has a space heating need (at outside temperatures below 12 °C)”. In heating mode, the EAHX provides only a fifth of what the RHX contributes. Measured energy gains expressed per unit area of wall surface of the ground tubes 15 kWh/m² in heating and 96 kWh/m² in cooling. The paper concludes by mentioning that “the EAHX alone is not suited to effectively cool a building during warm weather. It merely eliminates ventilation heat gains and should be combined with other measures that reduce room cooling loads, in order to help avoid the need for active cooling”.

Jautard Y and Trombe A (2003) Dimensionnement du “puits climatique”. Rapport final Prebat Ademe 04 04C 000 1. Downloadable from the Ademe web site, www.ademe.fr.

Commercial building in Presles (Val d'Oise, France [climate zone 4A]).

Section F of this report contains several examples of long-term measurements of an EAHX installed in a retirement home. Fig. 18 shows measurements performed during the summer, where the daily dampening of temperature oscillations is clearly evidenced (the graph also shows that it would be beneficial to bypass the EAHX at night, since lower temperatures could be obtained if outside air was used directly). Fig. 22 presents measures done during a winter period and shows the warming effect of the EAHX, as well as the long-term decline of air temperature delivered by the EAHX. Figure 23 shows one year of measurements. Section G contains similar figures for another system installed in an office building in Montigny-lès-Cormeilles, France.

Lee KH and Strand RK (2006) Implementation of an Earth Tube System into EnergyPlus. *SimBuild 2006 Conference*, 2-4 August 2006, MIT, Cambridge, Massachusetts. IBPSA-USA. Downloadable from http://www.ibpsa.us/pub/simbuild2006/papers/SBo6_058_066.pdf

Simulation paper

This is a simulation paper which describes the earth tube model in the EnergyPlus program. The paper does not contain validation data but the

⁴⁸ This is the same building as in Breesch H, Bossaer A and Janssens A (2005).

description of the model and the parametric study done for various climates (only in cooling mode, however) are interesting.

Lee TG (2004) Preheating ventilation air using earth tubes. Proc. 33rd ASHRAE Annual Conference, Portland, OR, 2004. Downloadable from <http://www.ucalgary.ca/files/evds/Earth%20tubes%20Tang%20Lee.pdf>

Summary paper.

The paper provides a general description of earth tubes but very little in terms of actual performance. Two interesting points are (1) the possible need to use fire-rated air supply ducts in some jurisdictions, and (2) limited pre-heating or pre-cooling performance due to the fact that the earth surrounding the tubes quickly cools down or heats up to the intake air temperature.

Ozgener L and Ozgener O (2010) Energetic performance test of an underground air tunnel system for greenhouse heating. Energy 35, 4079-4085.

Ozgener L and Ozgener O (2010) An experimental study of the exergetic performance of an underground air tunnel system for greenhouse cooling. Renewable Energy 35, 2804-2811.

Commercial system, near Izmir, Turkey [climate zone 3A]

These two papers contain some limited measured data for an agricultural EAHX. This is a closed-loop system located in a greenhouse. Measured extraction in heating mode is around 80 W/m with a COP of 5.16, whereas in cooling the capacity is around 245 W/m with a COP around 10.

Perino (2004) - see full reference under Haghighat (2004).

Pfafferott J (2003) Evaluation of earth-to-air heat exchangers with a standardised method to calculate energy efficiency. Energy and Buildings 35, 971-983.

Office buildings in Germany [climate zone 5A]

This paper deals mostly with office buildings so is of limited usefulness for this project, but it provides fairly extensive monitored data showing how EAHXs dampened the daily swing of outdoor temperatures. It discusses control strategies (timed or temperature-controlled), and mentions that energy gains by the EAHX do not necessarily translate in savings as the EAHX sometimes cools down the incoming air at low ambient temperatures and heat the incoming air at high ambient temperatures: better control strategies are required. The authors remark that the advantages of an EAHX are negligible in heating mode if a heat recovery ventilator is present; the only advantage is to avoid the danger of freezing of the heat recovery ventilator. The paper also provides performance indicators which range from 16 to 51 kWh/m²/year in heating and 12 to 24 kWh/m²/year in cooling. COPs are reported in the range 20 to 266.

Santamouris M (2006) Ventilation Information Paper no 11. Available from Air Infiltration and Ventilation Centre, www.aivc.org.

Summary paper.

The author has published quite a bit on the subject of EAHXs and seems to be an authority on earth tubes. In this short paper he describes general guidelines for earth tubes (construction, spacing of tubes, etc.) for cooling applications. He proposes a control strategy for EAHX: (1) temperature at the exit of the pipes has to be at least 3-4°C lower than indoor temperature, and (2) energy spent for the circulation of air is much lower than the cooling power offered by the system. The paper also reviews some monitored data for EAHX (commercial and residential) which show the systems to be generally effective. In one residential application the temperature differential due to earth tubes was found to be 10°C. However the paper mentions another project where the cooling power is reduced by half after one to three days of uninterrupted use, presumably because of the gradual heating of the earth surrounding the pipes.

Sharan G and Ratan R (2003) Performance of Single Pass Earth-Tube Heat Exchanger: An Experimental Study. IIMA Working Papers WP2003-01-07, Indian Institute of Management Ahmedabad, India. Downloadable from <http://www.iimahd.ernet.in/publications/data/2003-01-07GirjaSharan.pdf>

Commercial system in Ahmedabad, India [climate zone 1A].

This paper presents measurements from a 50 m long EAHX used for cooling and heating. Tests were limited to three consecutive days in each month. In cooling mode the system operated for 7 hours during the day and was shut down at night. In heating mode the system was operated for 14 hours during the night. The paper suffers from inconsistencies (for example, is the blower 300 W, 400 W, or 572 W?) and it is not clear whether the system is operated year-round or just 3 days a month during the tests (the latter being more likely). Nevertheless the temperature differential is found to be up to 14°C both in heating and cooling, with a mean COP of 3.3 in cooling mode and 3.8 in heating mode. These numbers would correspond to heat transfers of 1 kW in cooling and 1.14 kW in heating, or 20 W and 23 W per linear m of EAHX.

Staahl F (2002) Preheating of Supply Air through an Earth Tube System – Energy Demand and Moisture Consequences. Building Physics 2002 – 6th Nordic Symposium. Available for download from:

http://www.ivt.ntnu.no/bat/bm/buildphys/proceedings/67_Staahl.pdf

Simulation and air quality paper. Stockholm, Sweden [climate zone 6A].

The focus of this simulation paper is the quality of the air coming out of earth tubes, particularly related to the moisture content. The author notes that the material of the earth-tube wall is of great importance since it determines the moisture transfer: for example concrete will let the moisture through, plastic will not. For that reason the relative humidity predicted by the author for a

concrete tube is 100% year round. For a plastic tube it reaches 100% only in summer in a Nordic climate. Over half the year the relative humidity is above 80%, which is conducive to mold growth. The paper also mentions mold growth in two of three Swedish schools equipped with earth tubes. On the energy side, the author predicts (through simulations) that an earth tube will typically deliver 1,200 kWh/yr to a house in the Swedish climate, or about 10% of the heating needs.

Stecher D and Klingenberg K (2008) Design and performance of the Smith House, a passive house. ASHRAE Trans, 114, 1, 209-217.

Residential system, Urbana, IL [climate zone 5A]

This article reports on the performance of a Passive House⁴⁹. The house includes a 30-meter EAHX buried at least 2 m below grade. In winter the EAHX is used for frost protection of the HRV and to preheat / precool the air delivered to the house. Savings from 'free' frost protection are estimated at 125 kWh per year. Heating contribution is estimated at 10% of the annual heating energy consumption. However given the installation cost of \$2,300, these amounts of energy are too small to make the tube cost-effective. In summer the EAHX provides some cooling but the paper notes that the earth tube is inadequate for dehumidifying the air in the hot and humid climate of the Midwest. No formal measurements of air quality were done, but the paper mentions "a musty odor in the spring and fall, most likely due to a thin film of moisture forming on the inside walls of the tube", and the necessity to pump out condensates in the summer.

Thanu NM, Sawhney RL, Khare RN, Buddhi D (2001) An experimental study of the thermal performance of an earth-air-pipe system in single pass mode. Solar Energy 71 (6) 353-364.

Commercial system, India.

This paper deals with monitoring of a non-conventional (brick) EAHX used to heat and cool a farm house in India. The coefficient of performance of the system is found to be between 4.5 and 7.9 in summer, and 2.1 in winter.

Tittelein P, Achard G and Wurtz E (2009) Modelling earth-to-air heat exchanger behaviour with the convolutive response factors method. Applied Energy 86, 1683-1691.

Residential system, Chambéry, France [climate zone 4A].

This is a simulation-only paper, but it is interesting because of its conclusions for a 100 m² house: the effect of the EAHX on the heating demand is low (2 to 3 kWh/m²/year) when an HRV is used, because the EAHX and the HRV both preheat the air entering the building. Without HRV, gains of 9 to 12

⁴⁹ This is the same house described in EDU 2004, and EDU 2007.

kWh/m²/year could be expected. In summer however the system does provide improved comfort.

Trombe A, Pettit M and Bourret B (1991) Air cooling by earth tube heat exchanger: experimental approach. *Renewable energy* 1, 699-707.

Residential system near Toulouse, France [climate zone 4A]

This early paper describes experimental results for a house equipped with an EAHX. Different flow rates and schedules were tried. The paper notes that stopping the fan at night in summer gives time to the earth to replenish its cooling power. Cooling power was measured at 1.5 kW.

Voss K, Herkel S, Pfafferott J, Löhnert G, and Wagner A (2007) Energy efficient office buildings with passive cooling - Results and experiences from a research and demonstration programme. *Solar Energy* 81, 424-434.

Commercial systems in Germany [climate zones 4A-5A].

This paper presents monitoring results for a number of low-energy office buildings, which relied on number of techniques (night ventilation, slab cooling) to avoid active cooling. 9 of these buildings had EAHX. Although the application is not residential, the article is interesting insofar as it provides COP values which range from 20 to 280, while mentioning that the large range shows the need for quality assurance in the design phase and in building commissioning.

Wagner R, Beisel S, Spieler A, Vajen K and Gerber A (2000) Measurement, Modeling and Simulation of an Earth-to-Air Heat Exchanger in Marburg (Germany), 4th ISES Europe Solar Congress, Copenhagen, Denmark.

Commercial system near Marburg, Germany [climate zone 5A].

This paper presents one year of measurement results for a passive office building. The EAHX operates year-round and is coupled with an HRV that can be partially or completely bypassed. The system was subjected to air quality tests and it was found that the germ density was decreased by a factor of 40 compared to the outside air, because of the use of filters. The monitoring reveals no thermal exhaustion of the ground over the year. However the fact that the EAHX is run without any bypass all year has some unfortunate effects, such as cooling during some winter days and heating during some summer days. The amount is significant: in winter, the EAHX provides 6.2 MWh of heating but this has to be reduced by 2.5 MWh of unwanted cooling for a net contribution of 3.7 MWh. Similarly in summer the cooling contribution of the EAHX is reduced by more than half because of unwanted heating. Finally the paper shows that the EAHX contributes much less than the HRV - in heating mode, 5.3 MWh for the EAHX vs. 54.2 MWh for the HRV. The paper also provides the cumulative distribution function of the ΔT (outlet minus inlet) of the EAHX, which reveals that more than 50% of the time the ΔT is less than 2 °C.

6.2 Books, manuals, and norms

CETIAT (2008) Les puits canadiens/provençaux, guide d'information. Downloadable from <http://www.cetiat.fr/fr/publicationsveille/servezvous/guidesgratuits/index.cfm>.

This guide provides a good overview of the principles, design and operation of EAHXs. It mentions the need to use a bypass when outside temperature is between 10 and 20 °C. However it does not indicate the energy gains expected from such systems.

European Norm EN15241. Ventilation for buildings – Calculation methods for energy losses due to ventilation and infiltration in commercial buildings. See preview at <https://www.astandis.at/shopV5/Preview.action;jsessionid=4F65F33217D6FFD1839C49CBC50892DE?preview=&dokkey=271290>

This document contains in Annex A a simplified model of a ground to air heat exchanger.

Herzog B (2010) Le puits canadien. Eyrolles, ISBN 978-2-212-12723-2.

The author is also behind the site www.batirbio.org, which contains some of the same information as the book. The first half of the book is devoted to topics such as thermal comfort and ventilation. The book then describes EAHX associated with mechanical ventilation and with HRVs. The respective simulated contributions of ET and a 90% efficient HRV are summarized in this table (p. 43) for different climates:

Site	Annual savings from HRV (kWh/year)	Additional savings from EAHX (kWh/year)
Mulhouse	6,960	1,666
Paris	6,446	1,036
Rennes	6,339	802
Nîmes	4,706	459

This shows that when coupled to an HRV, the contribution of EAHX is usually modest (10 to 25% of the savings attributed to the HRV). On the other hand, when used for cooling, the potential of an EAHX is typically 3 kW with a COP ranging from 15 to 25. The book also mentions the need to over-size the EAHX ventilation in summer to provide more cooling. The book recommends the use of EAHX in cold locations (for preheating) and hot locations (for summer cooling) but not in temperate locations. It mentions the need to bypass the EAHX in the mid-season or whenever it is not beneficial, although it

recommends always leaving a residual air flow to prevent the growth of mould and bacteria. The book also summarizes results of bacterial testing performed by Barbara Flückiger at ETZ Zürich, who showed that, except in one case, the concentration in mould and bacteria in the air delivered to the house is actually lower than that in the outside air (this is due to filters at the entrance of the EAHX and the ventilation system). The lone exception is due to a poorly design system (corrugated pipe, insufficient flow of air).

Jauffrit O (2010) Le puits canadien - du concept à la mise en oeuvre. ISBN 978-2-7466-1481-9. Downloadable from <http://www.autoconstruction.info/-Puits-Canadien-.html>.

This guide is written for do-it-yourself builders who want to build their own earth tube system. This document is of very limited interest.

Loyau F (2009) Puits canadien et ventilation basse énergie. Éditions L'inédite, ISBN 978-2-35032-145-5.

The author of this book is the CEO of Fiabiat Concept, a French company specialized in green buildings which has installed a number of residential EAHX. The book is an expanded version of what is available on the company web site⁵⁰. It provides a wealth of information about the principles, design and operation of EAHXs. It stresses that there is not one solution that fits all - a case-by-case approach is needed depending on local climatic conditions, the air tightness of the house and the type of ventilation used, and the local regulation for required ACH. The book suggests that an EAHX becomes interesting for heating if the differential between ground and outside air temperatures is greater than 10°. There is generally a need to bypass (either manually or automatically) the EAHX in mid-season. Using an EAHX when the envelope is not tight is usually not effective as it will not change appreciably the energy consumption. EAHXs work well with regular mechanical ventilation systems. With HRVs, the interest of the EAHX is mainly to provide antifreeze protection to the HRV and free cooling in the summer; in winter, it is more economical to use a higher performance HRV than to couple a medium performance HRV with an EAHX. The book concludes with three case studies (passive house, solar house, and cooling application). The last chapter of the book provides an analysis of a system installed in 2007 (EAHX + high efficiency HRV), used exclusively in heating mode. The EAHX delivered around 1,500 kWh/year with a COP of 6.3 based on the amount of energy used by the HRV.

VDI (2004) VDI 4640 - Part 4: Thermal use of the underground - Direct uses.

These guidelines from the Verein Deutscher Ingenieure (Association of German Engineers) has a whole section on air heating or cooling in the underground. It mentions the use of EAHXs for frost protection, that EAHX make sense only when not more than the required outside air rate for the building is delivered,

⁵⁰ <http://www.fiabiat.com/puits-canadien.php>

and that a bypass is required. It also reports that that performance factors are in the 6 to 12 range when air is moved by a dedicated mechanical system, 20 to 50 in the case of an otherwise existing ventilation system. It mentions that for a small office building, a ground-coupled heat exchanger with a 3,600 m³/h flow rate, annual savings of 8,350 kWh/year for heating and 3,470 kWh/year for cooling were obtained. Temperature gains can be 12 to 14°C in heating and somewhat lower in cooling. The document explains in detail how to calculate performance indicators to evaluate the performance of the system in heating, in cooling, and year-round.

The document provides detailed guidelines for the design of small systems for residential buildings with flow rates up to 1000 m³/h (another section deals with larger buildings). It mentions that installing an EAHX upstream of a heat recovery unit brings virtually no improvements in thermal output, although it provides frost protection and moderate summer-time cooling.

The document also provides guidelines for installation, selection of materials, and dismantling, and a section on recommended control strategies, which can be fairly complex; it recommends that the system be operated only when the energy gain (in cooling or heating) exceeds the energy used to drive the fan; a rule of thumb is that the temperature differential between inlet and outlet has to be greater than 2°C.

The document gives a method to evaluate the economic benefits of the system, and mentions that in heating mode EAHXs are generally less interesting than HRVs, but that they may make a greater contribution in summer by cooling or pre-cooling the air for the building.

6.3 Internet resources

There are many sites with information about earth tubes. Not all contain new or useful information, but here is a list of the most interesting ones (English and French):

http://fr.wikipedia.org/wiki/Puits_provençal

http://en.wikipedia.org/wiki/Earth_cooling_tubes

Introductory articles about EAHX.

http://fr.ekopedia.org/Puits_canadien

A general site about EAHX (in French).

<http://www.fiabitat.com/ventilation.php>

Web site of a French company designing and installing EAHXs. One of the owners of the company, F. Loyau, is the author of *Puits canadien et ventilation basse énergie* (see Loyau, 2009). Large parts of the books are available at <http://www.fiabitat.com/puits-canadien.php>.

<http://www.batirbio.org>

This site is maintained by Bruno Herzog (author of *Le puits canadien*, see Herzog, 2010) and contains a significant amount of information from the book.

<http://www.canada-clim.com/>

This site is from a company devoted to the development and installation of EAHX. The site shows examples of installations made by the company, mostly in the institutional sector, and some measurement results in summer and winter. The measurements illustrate clearly the tempering effects of an EAHX during summer and the year-round performance of EAHXs.

<http://www.zigersnead.com/current/blog/post/what-is-a-ground-air-heat-exchanger/09-15-2010/2560/>

A note about EAHX, from a American architectural firm, with some examples of installations.

7 Appendix B - System manufacturers

A number of manufacturers of pre-designed systems were identified. However, few actually have been used in Canada to provide evidence of their performance in the Canadian climate.

Name	REHAU ECOAIR ground-air heat exchange system
Manufacturer	REHAU
Web info	http://na.rehau.com/construction/renewable.energy/ground-air.heat.exchange/ground-air.heat.exchange.shtml
Brochure	Yes
Characteristics	System includes stainless steel air inlet with air filter, solid PVC pipes and fittings with anti-microbial coatings, and condensation management drain.
Price	N/A
Notes	Installed in BioHaus at the Concordia Language village in Bemidji, MN, in the David Suzuki school in London, ON, in the Lepape residence in Nelson, BC, and the Malagash house in NS.
Name	Geo Power System
Manufacturer	Geo Power System Co
Web info	http://www.geo-power.co.jp/en/index.htm
Brochure	Yes
Characteristics	Concentric pipes go vertically to 5 m underground.
Price	N/A
Notes	System was tested in Ottawa by Natural Resources Canada but data is not available (confidential client report).
Name	Hegler HEKATHERM PE-HD heat exchanging system
Manufacturer	Hegler
Web info	http://www.hegler.de/set_grafix/download/prospekte/Hekatherm-englisch-low.pdf
Brochure	Yes
Characteristics	PE-HD twin wall, 200 mm diameter coiled pipe; air inlet chamber; condensate chamber; distributor chamber.
Price	N/A
Notes	Not distributed in North America.
Name	Terra-Air-Home
Manufacturer	Fränkische
Web info	http://www.fraenkische.com/cps/rde/xchg/fraenkische_int/hs.xsl/14257_14308_ENG_HTML.htm ; see also

	http://unegrangengaume.be/medias/fichiers/puit-canadien-terra-air-home.pdf
Brochure	Yes
Characteristics	100 metres of PE pipe, suction and inspection shafts, suction element, pipe lead-through, and connecting accessories essential to ensure water tightness.
Name	Kits puits canadien Helios
Manufacturer	Eole
Web info	http://www.eole-fr.com/Kits_Puits_Canadiens/Tout_Les_Kits_Puits_Canadiens.php
Brochure	Yes
Characteristics	Variety of kits connected to ventilators or HRV. Also provides water-based systems.
Price	€1,390 to 6,990 (\$1,990 to \$10,000) depending on number of tubes, accessories, etc.
Notes	The site http://www.eole-fr.com/ has a fair amount of information about earth tubes
Name	Geoventilation
Manufacturer	Unelvent
Web info	http://www.unelvent.com/geoventilation-puits-canadien-provencal.html
Brochure	Yes
Characteristics	Includes both residential and industrial systems.
Price	Depends upon options selected.
Notes	The tubes appear to be provided by Rehau.
Name	Thermie-Duct
Manufacturer	VIM
Web info	http://www.vim.fr/element.asp?ID=1390
Brochure	Yes
Characteristics	This is a REHAU system sold under a different name.
Price	N/A
Notes	
Name	ComfoFond - Erdwärmetauscher
Manufacturer	Zehnder
Web info	http://www.zehnder-online.de/comfosystems/ComfoFond---Erdw%C3%A4rmetauscher,13.html In North America: http://www.zehnderamerica.com/products/comfofond.asp
Brochure	Yes
Characteristics	Two products: ComfoFond (air-based) and ComfoFond-L (brine

Price	loop).
Notes	N/A
Name	Ryb Terra System
Manufacturer	Ryb Terra
Web info	http://www.rybterra.fr/index.php/terra-system
Brochure	Yes
Characteristics	
Price	N/A
Notes	
Name	Puits Canadiens Westaflex
Manufacturer	Artklima
Web info	http://www.artiklima.be
Brochure	No
Characteristics	
Price	N/A
Notes	
Name	sole-ewt
Manufacturer	netec Energietechnik
Web info	http://www.sole-ewt.de/index-e.html#CWK
Brochure	Yes
Characteristics	Brine operated ground heat exchangers with highly efficient heat recovery
Price	N/A
Notes	Website contains some monitored data (in German).

8 Appendix C - Software

There are many tools that can be use to design and simulate EAHXs, here are four of the most complete ones:

WKM

<http://www.hetag.ch/huber/download/indexfr.htm>

GAEA

http://nesa1.uni-siegen.de/index.htm?/softlab/gaea_e.htm

http://nesa1.uni-siegen.de/index.htm?/produkte_e.htm

TRNSYS

<http://sel.me.wisc.edu/trnsys/>

EnergyPlus

<http://apps1.eere.energy.gov/buildings/energyplus/>

9 Appendix D - ASHRAE Climate zones

ASHRAE climate zones are defined in ASHRAE Standard 169. They are based mainly on heating and cooling degree days considerations, with additional sub-zones (dry, humid, marine) defined based on precipitation. They provide a quick way to describe the type of climate experienced at a site. The following list can be used to find Canadian locations having roughly the same climatic conditions as some of the sites outside of Canada mentioned in this report:

Zone 1A: Very hot - humid

This zone has no equivalent in Canada.

Zone 3A: Warm - humid

This zone has no equivalent in Canada.

Zone 3C: Warm - marine

This zone has no equivalent in Canada.

Zone 4A: Mixed - humid

Vancouver and Victoria are in zone 4, although they have a more marine climate.

Zone 5A: Cool - humid

This zone includes for example south-western Ontario (e.g. Windsor and London), and some parts of BC (Kelowna and Port Hardy).

Zone 6A: Cold - humid

This zone includes the north-western part of BC (Terrace, Revelstoke, Quesnel), southern Alberta (Lethbridge, Medicine Hat), locations along the lower St Lawrence River (Montreal, Trois-Rivières), most of Nova Scotia, eastern New Brunswick, and the south-eastern coast of Newfoundland.

Zone 7: Very cold

Climate zone 7 includes Prairies locations south of 55°N (Calgary, Regina, Winnipeg), some northern Ontario locations (Thunder Bay, Sudbury) and some parts of Quebec (Quebec City).

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