Methodological approach for a sustainable management of water inflow and geothermal energy in tunnels

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Approccio metodologico per uno sfruttamento sostenibile delle venute d'acqua e dell'energia geotermica nelle gallerie

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Riassunto: Nella progettazione delle gallerie raramente vengono presi in considerazione tutti i possibili utilizzi delle risorse sotterranee che si incontrano durante lo scavo. In questo articolo si è tentato di analizzare la natura e possibilità di utilizzo delle risorse di tipo geotermico. Esse sono essenzialmente rappresentate dall'infiltrazione di acqua calda o fredda all'interno della galleria e dalla temperatura stessa dell'ambiente di scavo. Lo studio ha consentito di proporre un approccio metodologico per la formulazione del problema al fine di organizzare le informazioni necessarie e riuscire ad avere una stima dell'effettiva attrattività dell'utilizzo. L'approccio metodologico è quindi stato applicato al caso studio della linea metropolitana Dudullu-Bostanci di Istanbul, attualmente in corso di progettazione, ipotizzando una possibile applicazione di scambiatori di calore integrati all'interno del rivestimento della galleria e valutandone in via preliminare gli aspetti economici ed ambientali.

Parole chiave: energie rinnovabili, geostrutture energetiche, progettazione sostenibile.

Keywords: *renewable energy, energy geostructure, suistanable design.*

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Abstract: *It is quite unusual to consider the exploitation of geothermal resources during at the tunnel design stage. This paper is intended to analyse the nature and the potential of the geothermal resources. These are essentially the hot or cold water inflow and the temperature of the surrounding ground itself. A methodological approach is proposed to face the problem, determine relevant information and estimate the attractiveness of the application. The approach is then applied to the case study of the metro line Dudullu-Bostanci in Istanbul, currently under design, by identifying a possible application of heat exchangers integrated into the tunnel lining and evaluating preliminarily the environmental and economical aspects.*

Introduction

The impact of climate change is being increasingly concrete and difficult to manage, with the occurrence of extreme weather events that have a strong negative impact on land protection. The emissions of harmful gases in the atmosphere that affect the natural dispersion of the infrared radiation emission from the Earth's surface are claimed to be the main cause of climate changes. The polluting gases are produced largely from road traffic, domestic heating and industrial activities, for this reason the investment policy of the industrial countries is moving towards reducing emissions of pollutants into the atmosphere (Rio de Janeiro 1992, Berlin 1995, Kyoto 1997, Copenhagen 2009). Renewable energies have experienced in recent years a strong and constant growth, including Geothermal Energy. Electric energy is currently produced by converting heat thanks to turbo generators. Heat is extracted at depths that are economically feasible. However, heat extracted may also be used for domestic heating or to produce hot water. This is currently done with closed circuit systems or by retrieving water from wells and re-injecting it in the aquifer after heat exchange. Water inflow during tunnelling can be used to this purpose. Moreover, underground geotechnical structures, such as deep and shallow foundations, diaphragm walls, tunnel linings and anchors are being increasingly employed to exchange heat with the ground and supply thermal energy for heating and cooling of buildings and de-icing of infrastructures (Laloui and Di Donna 2013). The thermal activation is achieved by installing absorber pipes in the geostructures, in which a circulating fluid extracts or injects heat from or into the ground (Adam 2009; Brandl

2006, Markiewicz & Adam 2009, Frodl et al. 2010, Franzius and Pralle 2011, Banks 2012, Lee et al. 2012, Nicholson et al. 2013, Barla & Perino 2014a, Barla & Perino 2014b, Barla & Di Donna 2015).

In the case of tunnelling, it is not unusual that hot or cold water inflows are encountered, as well as relatively high temperatures of the ground. Unfortunately, exploitation of these resources is not a common practice and is rarely conceived from the design stage. However, in recent years, the growing awareness to this topic is bringing the legal framework to define the exploitation of natural resources as compulsory.

This paper aims to provide a methodological approach for the exploitation design of the natural resources made available by the tunnel excavation, to be integrated with the usual design procedures for tunnels construction. The possibilities in tunnelling essentially include the exploitation of the hot water inflow, via heat pumps for buildings heating, the exploitation of the cold water inflow for drinking, industrial or irrigation uses and the exploitation of thermal inertia of the subsoil via heat exchangers (Dematteis et al. 2007). In the following, the steps needed to investigate the potential application are presented. The methodological approach is then applied to the case study of the Istanbul metro line Dudullu-Bostanci, currently under design, by identifying a possible application of heat exchangers integrated into the tunnel lining and evaluating preliminarily the environmental and economical aspects.

Methodological approach

Exploitation of hot water inflow

Hot water intercepted by tunnel excavation ($T > 25°C$) can be used directly or via a heat pump for building heating. A preliminary assessment for this application should go through the following steps:

1. Identification of the parameters of interest that influence the exploitation. These are essentially (a) the rate of the hot water inflow that could be defined with empirical, analytical and/or numerical methods, and (b) the temperature of the groundwater, that could be predicted with the geothermal model;
2. Assessment of the different parameters thanks to (a-I) permeability test, (a-II) water potential head measurement with piezometer to define the flow rate of water and (b) determination of temperature with thermal log measurement;
3. Definition of the construction requirements necessary to improve the performance of the exploitation such as (a) punctual drainage systems that have to be constructed outside the alignment of the tunnel, (b) the construction of separate collection pipes for inflow water in order avoiding mixing with other water sources and (c) the connection to the end user that can be direct or via heat pumps;
4. Prediction of the potential of the system. This requires computing the heat losses from the catchment point to the end users by the following equation:

$$T(L)=T_e+(T_0-T_e)e^{-KL/QC}$$

where: L is the length of the pipe, T_0 and T_e are the temperature at the beginning of the pipe and in the tunnel, Q is the flow rate [l/s], K [W/mK] is the transfer coefficient and C is the thermal capacity of water [J/lK]. Additionally, the effective evaluation of the heating power estimated in thermal MegaWatt (MWt) obtained as:

$$P(MW_t)=C\ Q\ \Delta T$$

where: C is the specific heat capacity of water [$4.2\ 10^3$ J/l K]; Q is the water flow rate [l/s]; and ΔT is the useful temperature ($T-T_0$) of the tunnel water [°C].

Exploitation of cold water inflow

Cold water inflow ($T < 25°C$) can be used for drinking, industrial or irrigation purposes. A preliminary assessment for this measure will go through the following steps:

1. Identification of the parameters of interest. These are (a) the flow rate of the water inflow and (b) the chemical composition of water that has to be compared with the legal constraints to define the possible exploitation as drinking water;
2. Assessment of the different parameters thanks to (a-I) permeability test, (a-II) water potential head measurement with piezometer to define the flow rate of water; (b) laboratory tests that can be divided in chemical analysis to determine the chemical composition of water, and microbiological analysis to determine the presence of bacteria and parasite concentration at specific temperature; (c) geographic analysis of the region around the capitation point in order to verify that all the destinations use of any zone are respected;
3. Definition of the construction requirements necessary to improve the performance of the exploitation are (a) the installation of drains in the rock mass, which represent an additional cost to the excavation of the tunnel. The drains are essentially composed of windowed pipes placed inside pre-excavated boreholes. Another technical requirement needed for water exploitation is (b) the recollection room, that is a space where the drained water is collected and channelled into pipes. If the water is intended for drinking purposes the regulations state that this room must have the possibility to be inspected any time, in order to allow for controlling water composition and purity, whenever necessary. The last technical requirement is (c) the connection to the end user;
4. Prediction of the potential of the system. This requires determining the (a) flow rate in steady state condition, and an (b) estimated duration of this condition. It is also important to investigate the (c) influence of the construction on the hydrogeological scenery, because the tunnel construction may also modify water supply for drinking,

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irrigation and industrial uses, with major economic and social repercussions on wide neighbouring areas. Definition of a model can help to predict the possible future scenarios, but considering the complexity of the phenomena and the extension of the involved area, it is recommended to design a pre- and post-construction monitoring plan.

Exploitation by Tunnel heat exchangers

Thermal inertia of the subsoil can be used for heating and cooling of buildings provided heat exchangers are installed inside the tunnel (Barla & Di Donna 2015). A preliminary assessment for this application will go through the following steps:

1. Identification of the parameters of interest. These are essentially, the (a) groundwater flow rate [m/d] that contributes to the transport of heat by convection improving the potential of the system, the (b) temperature of the subsoil, which at the depth of concern is mostly constant throughout the year and the (c) thermal conductivity of the subsoil that influences the heating transport through conduction;
2. Assessment of the different parameters thanks to (a) flowmeter tests conducted at the excavation depth, (b) temperature measurements performed with thermal log and (c) laboratory tests on soil samples to determine the thermal conductivity of the soil;
3. Definition of construction requirements. These are the (a) integration of heat exchanger in the tunnel lining; (b) the creation of a closed circuit for the thermo-fluid, a glycol propylene mixed with water, and a (c) secondary equipment, i.e. heat and hydraulic pumps, to ensure the proper functioning of the system;
4. Prediction of the potential of the system. Di Donna & Barla (2015) have proposed a preliminary graphical approach (Fig. 1) to determine the heat extraction and injection potential, given the value of the ground water flow rate, the ground temperature and the thermal conductivity of the soil. These plots were determined with parametric three dimensional modelling based on a number of simplifying assumptions and conditions: the groundwater flow rate is perpendicular to the tunnel axis, the inlet water temperature is 4°C in winter and 28 °C in summer and its velocity is equal to 0.4 m/s.

Example of application to Istanbul metro

The methodological approach described above, limited to the exploitation by tunnel heat exchangers, has been applied to a case study in Turkey, the Istanbul metro line Dudullu-Bostanci which is currently under design (Fig. 2).

In order to compute the geothermal potential of the metro line, the total length has been divided in homogeneous sections from the geological point of view, determining the parameters of interest and the geothermal potential for each section.

Groundwater flow rate

The groundwater flow rate is influenced by the permeability of the medium and the hydraulic gradient applied. It is possible to determine the two parameters using an analytical approach derived from the Darcy's law. This has been done for each section of the tunnel.

The Lugeon tests were conducted to determine hydraulic conductivity of the rock formations while Lefranc tests were performed for soil formations. Average values were considered. The hydraulic gradient was estimated thanks to the hydrogeological map (Istanbul Metropolitan Municipality 2014).

Ground temperature

The soil temperature is considered to be equal to the average value of the seawater temperature in Istanbul. This was considered reasonable because water has higher thermal inertia than air and the metro line runs close to the sea and mostly below the water level. The average value of the temperature is 17 °C, corresponding to the average between the cooling period (14,3 °C) and the heating period (19,8 °C).

Thermal conductivity

Thermal conductivity was determined thanks to correlation with the Uniaxial Compressive Strength, (UCS) of the

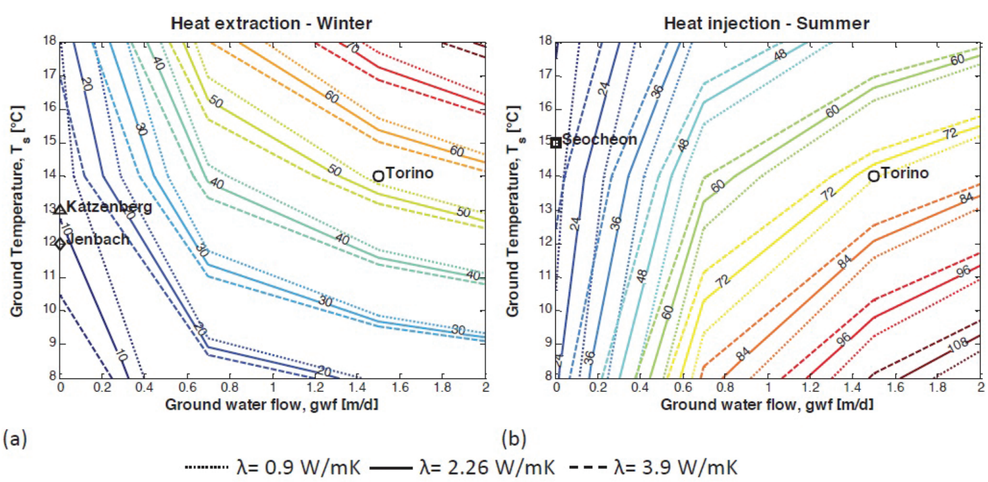

Fig. 1 - Design chart for winter and summer mode (heat injection/extraction in W/m²) (Di Donna &Barla 2015).

Fig. 1 - Grafici parametrici per la definizione del potenziale termico invernale ed estivo (Calore estratto/iniettato W/m²) (Di Donna & Barla 2015).

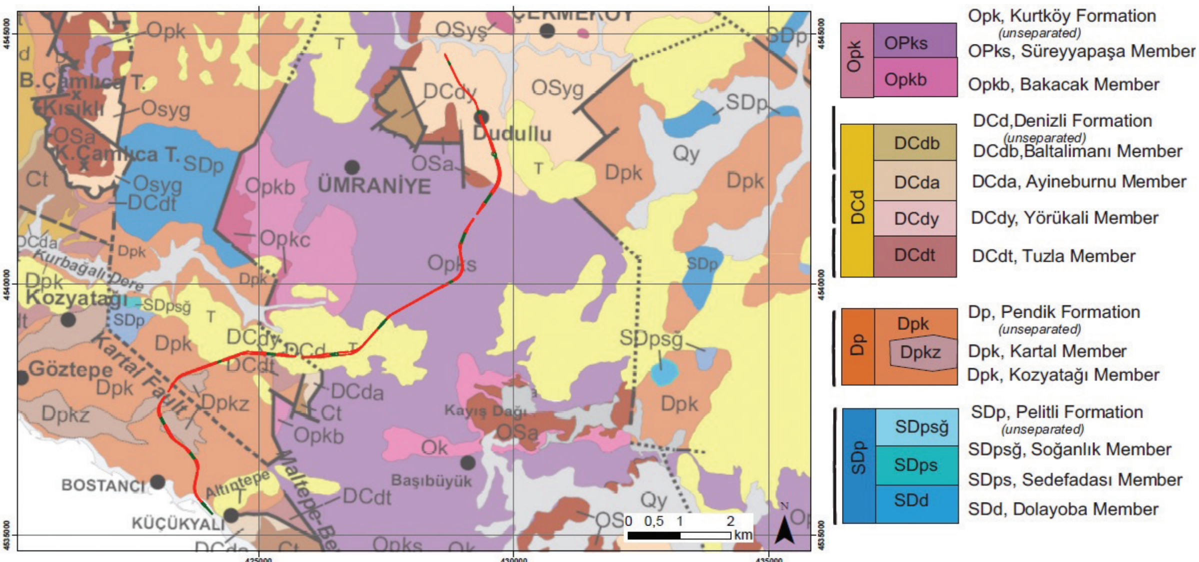

Fig. 2 - Metro plan superimposed to the geological map of the eastern part of Istanbul Municipality, the Asian side.

Fig. 2 - Tracciato metro sovrapposto alla carta geologica della parte Est della città di Istanbul, la zona Asiatica.

ground, according to Yasar (2008). Values are given in figure 3 as a function of the chainage. The geothermal potential was evaluated only for the section with higher value of thermal conductivity (PK from 8.8 to 9.6 km).

Geothermal potential

The design charts of figure 4 were directly used for the evaluation of the heating potential for the most promising section of rock formation (with higher conductivity) and soil (with higher permeability). Data are shown in table 1.

The geothermal potential is higher for Section B (Tab. 2), both in heating and cooling mode, thanks to the flowrate that increases heat transport by convective transport.

The absorber pipes consist of cross-linked high resistance polyethylene (PE-X). The external diameter of the pipes is 25 mm and the average spacing of the absorber pipes is between 25 to 30 cm. A good compromise between the efficiency of the system and its encumbrance was found to be obtained by joining together 5 rings in series to form a single circuit and then connect each circuit in parallel with the others (Barla & Di Donna 2015). The tunnel diameter is 6.3 m and the longitudinal thickness of the ring is 1.4 m. Therefore each circuit of 5 rings is 7 m long. Based on these figures, a group of 20 circuits, covering a total length of 140 m, will need 20 inlet and 20 outlet pipes, resulting in two equivalent tubes of 12.5 cm of diameter (Fig. 5).

PK	tc
0,3	0,74
1,45	0,55
1,85	0,55
2,25	0,49
2,65	0,32
3,35	0,43
4,05	0,51
4,55	0,74
5,2	0,1
6,65	0,17
8,3	1,09
9	1,19
9,3	1,1
9,5	1,1
10,5	0,49
12,1	0,4
13,05	0,07

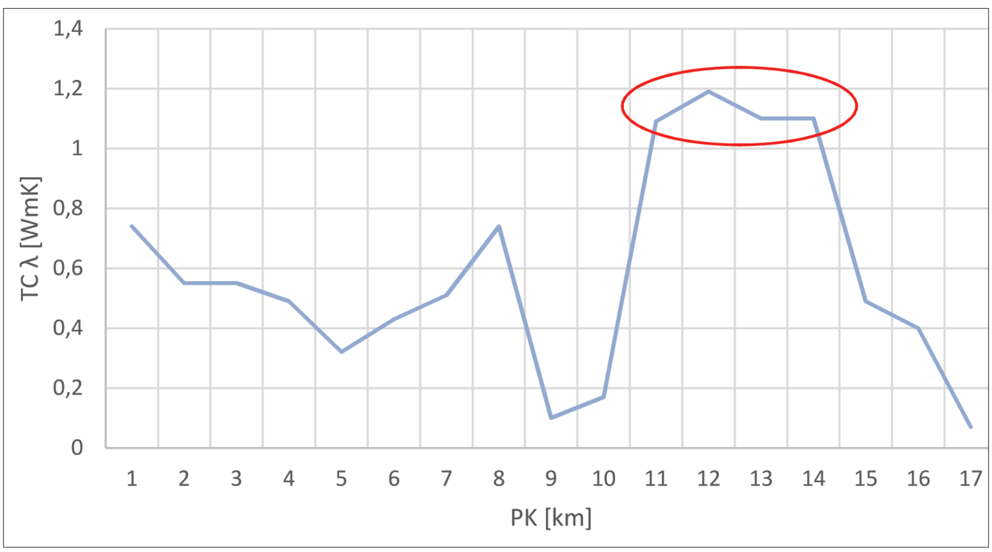

Fig. 3 - Thermal conductivity versus chainage.

Fig. 3 - Andamento capacità termica rispetto alla progressiva del tunnel.

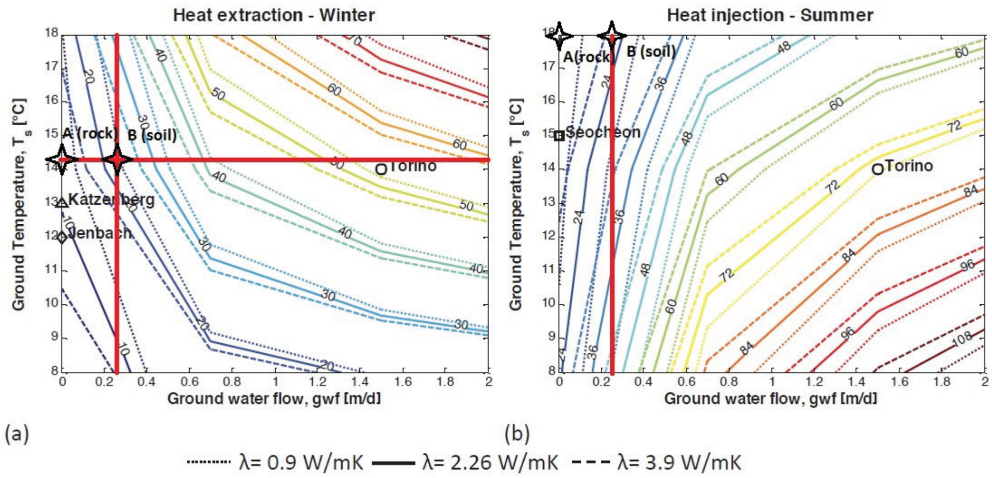

Fig. 4 - Evaluation of heat extraction (a) and injection potential (b) for most promising section of the metro track, according to Di Donna & Barla (2015) design charts.

Fig. 4 - Valutazione del potenziale di estrazione ed iniezione calore per le sezioni del tracciato più promettenti, utilizzando i grafici parametrici di Di Donna & Barla (2015).

Tab. 1 - Heating and cooling potential for most promising sections along the tunnel alignment..

Tab. 1 - Capacità di raffreddamento e riscaldamento per le sezioni più promettenti dell'intero tracciato della linea metro.

Section	Formation	PK [km]	Geological formation	Hydraulic conductivity k [m/s]	Flow rate v [m/d]	Thermal conductivity λ [W/mK]	Groundwater temperature	
							Heating [°C]	Cooling [°C]
A	Rock	8.8 - 9.2	Kurtköy	1.00E-06	~ 0	1.19	14.29	19.80
B	Soil	11.4 - 12.8	Sultanbeyli	2.60E-05	0.225	0.38	14.29	19.80

Tab. 2 - Heating potential (W/m²) for Sections A and B.

Tab. 2 - Potenzialità termica (W/m²) per le sezioni A e B.

Section	Heat extraction	Heat injection
A	10	15
B	20	20

Once the geometry of the problem is defined, it is possible to compute the total power generated by the system, based on the geothermal potential of the ground (20 W/m² both for heating and cooling) for the sector with higher potential.

Figure 6 illustrates the geological longitudinal section for section B that is the most interesting for heat exchanger application. The result is given in table 3 with reference to a 140 m and a 280 m length.

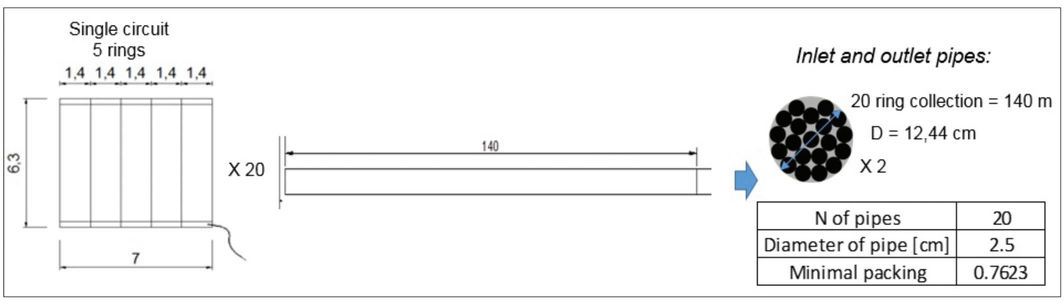

Fig. 5 - Geometry configuration of the heat exchanger system.

Fig. 5 - Configurazione geometrica del sistema di scambiatori di calore.

Tab. 3 - Heating power for Section B.

Tab. 3 - Potenza termica per la sezione B.

Heating potential [W/m²]					Heating power [kW]	
Winter	Summer	Number of equivalent tube	Tunnel diameter [m]	Length of installation [m]	Winter	Summer
20	20	2	6.3	140	55.4	55.4
20	20	4		280	110.8	110.8

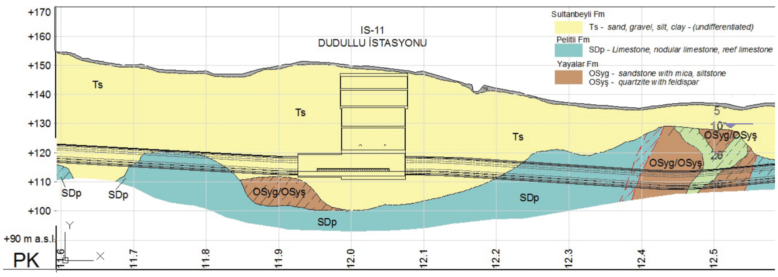

Fig. 6 - Geological longitudinal section for Section B, black lines indicates the tunnel alignment and Dudullu station layout.

Fig. 6 - Sezione geologica longitudinale per il tratto B, con rappresentazione della sezione del tunnel e della stazione di Dudullu.

Considering an operating time of 6000 h per year (i.e. 3500 h for heating and 2500 h for cooling), the total annual energy produced by the system can be evaluated. The maximum building heat requirement for heating and cooling was assumed based on the Turkish Standard 825 (TS-825) which indicates a heating energy demand of 48 kWh/m^2, for this region, and a ratio between exposed surface and volume (A/V) less than 0.2. The specific cooling demand is set equal to 50 kWh/m^2. Finally table 4 shows the total annual energy and the computed equivalent surfaces that can be conditioned by transferring heat/cool to the buildings via a heat pump system.

Economical and environmental aspects

National and European regulations strongly support the reduction of CO_2 emissions in the energy market. It is of interest to estimate the equivalent reduction of CO_2 emissions which is achieved by the tunnel heat exchanger system. The computation is here performed only for heating mode, considering 1 km of tunnel length compared to typical gas boiler application.

The information needed are:

- the Coefficient Of Performance (COP) of the heat pump, assumed equal to 5;
- the annual electricity used by the heat pump to heat the water for the end user which can be determined dividing the annual energy produced by the heat exchanger system for the COP of the heat pump;
- the emission [gCO_2/kWh] for the electricity used in Turkey (Brander et al. 2011);
- the emission [gCO_2/kWh] for natural gas boiler (www.biomassenergycentre.org.uk).

The computed reduction in CO_2 emission is shown in table 5, compared to that for a Fiat 500 1.3 Diesel (www.ilsole24ore.com).

The estimation of installation costs was performed with reference to a length of 280 m. Main installation costs are due to pipes installation, those embedded in the lining and those of the primary circuit. The total cost for a length of 280 m was estimated to be approximately 50,000 € that corresponds to a price of construction of less than 200 €/m, which is negligible if compared to tunnel construction costs.

Conclusions

A methodological approach for the preliminary assessment of the exploitation potential of the heat resources that arise from tunnelling has been illustrated in this paper. This approach could be systematically integrated in the tunnel design practice in order to improve the sustainability of the construction itself.

The application to the Istanbul metro line allowed exemplifying the process of evaluation of the geothermal potential, in the case of heat exchangers. The environmental impact analysis allowed estimating a reduction of 37.5 tons of produced CO_2 compared to traditional heating systems for each km of installation.

More detailed field measurement, determination of input parameters and analysis are required for construction purposes but these results confirm the interest in investigating the use of tunnel lining to exchange heat with the ground, which apparently requires limited investment if compared to the costs of the infrastructure itself.

It is the Authors belief that the geothermal potential evaluation should be integrated to the design practice for future tunnel projects. Moreover, raising the awareness of the Public Authorities on these techniques may be decisive to improve the exploitation of the heat resources in tunnelling.

Tab. 4 - Total annual energy and heated/cooled surface for different length of installation.

Tab. 4 - Energia annua totale prodotta e superficie che è possibile riscaldare/raffreddare con diverse lunghezze di applicazione.

	Total annual energy [MWh]					
Length of application [m]	Winter	Summer	Building heating demand [kWh/m^2]	Heated surface [m^2]	Specific cooling demand [kWh/m^2]	Cooled surface [m^2]
140	194.0	138.5	48	4,041	50	2,771
280	387.9	277.1		8,082		5,542

Tab. 5 - Emission of CO_2 avoided with 1 km heat exchanger application for heating purpose.

Tab. 5 - Riduzione di produzione di CO_2 con l'applicazione di 1 km di scambiatori di calore per la sola funzione di riscaldamento.

Emissions for electricity in Turkey [gCO_2/kWh]	1009.75		
COP heat pump	5		
	Winter	Summer	Total
Electricity need [kWh]	277088.47	-	277088.47
Emissions for GSHP heating [kgCO_2/year]	279790.15	-	279790.15

Natural gas boiler CO_2 production [gCO_2/kWh]	229		
	Winter	Summer	Total
Heat needed [kWh]	1385442.4	-	1385442.36
Emissions for natural gas boiler [kgCO_2/year]	317266.30	-	317266.30

CO_2 savings [t]	CO_2 emission Fiat 500 [kg/km]	Equivalent km covered	Earth circumference [km]	Number of round the world
37.48	0.11	340692.26	40075	9

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