LONG-TERM MEASUREMENTS OF ENERGY GEOSTRUCTURES AT THE TABORSTRAßE METRO STATION IN VIENNA

D. Adam, R. Markiewicz & A. T. Brunner
TU Wien, Vienna, Austria

ABSTRACT: For nearly twenty years, four metro stations within Vienna's U2 line extension opened 2008 have successfully utilized energy geostructures for heating and cooling. The Taborstraße station, which utilizes thermo-active diaphragm walls, piles, slabs, and tunnel sections, serves as a primary case study for this technology, supported by an extensive monitoring dataset. This paper evaluates the energy performance of the whole station using energy geostructures by comparing in-situ energy measurements against initial design simulations. The results indicate that while annual heating consumption aligns closely with original forecasts, the actual cooling demand remains significantly below predicted levels, revealing a substantial untapped thermal capacity in the infrastructure. Furthermore, the study identifies external influences on system performance, such as a notable decrease in heating energy during the 2022/23 season linked to socio-economic energy-saving measures rather than technical constraints. Ultimately, these long-term results confirm that integrated energy geostructures provide a robust and scalable solution for urban infrastructure, offering critical benchmarks for the design and optimization of future geothermal energy systems in urban environments.

1. INTRODUCTION

1.1 REASONS FOR THE USE OF GEOTHERMAL ENERGY

The use of near-surface geothermal energy has become increasingly important starting from the 1980s (Brandl 2006). This form of sustainable energy generation is an important contribution for reducing greenhouse gases and achieving the goals of the Kyoto Protocol or the Paris Agreement. The share of total energy used in the building and infrastructure sector is 42 % in the EU ("households" and "commercial and public services" in 2020 (Eurostat 2024a)), with about two-thirds of energy used in households for heating and cooling (Eurostat 2023). Consequently, the use of geothermal energy for these purposes seems to be highly reasonable, because this form of sustainable energy production is considered to be the most efficient form of building climatization (Yoon et al. 2015). Due to the current low share of renewable energy sources (23 %) for heating and cooling in the EU (Eurostat 2024b), there is a large potential for CO2 savings in this area, especially if renewable primary energy sources are used (Laloui & Rotta Loria 2019).

In addition, the use of geothermal systems offers the possibility of dual use, i.e., using a single system for both heating and cooling. Due to more efficient thermal insulation and rising air temperatures, the heating demand in Europe is steadily decreasing, while the cooling demand is increasing (Eurostat 2024c). Current strongly increasing energy prices as well as a decades long self-created dependence of the European Union (and especially Austria and Germany) on energy supplies from other countries (particularly gas imports from Russia) and the associated problems posed by planning uncertainties and loss of sovereignty (Rodríguez-Fernández et al. 2022) are all further arguments for the use of locally sourced geothermal energy.

Apart from energy piles (single piles), energy walls (diaphragm walls or bored pile walls) and energy bottom slabs are now increasingly used. These concrete components are collectively called "energy geostructures" or "thermo-active geostructures" (heat exchangers embedded in earth-coupled concrete structures, and in the majority of cases, foundation elements) and have several advantages over geothermal collectors installed close to the surface or conventional borehole heat exchangers. On the one hand, the corresponding components are needed anyway due to their structural function, which is why the additional costs for equipping them as geothermal heat exchangers are low (synergistic effects). Due to these larger dimensions compared to borehole heat exchangers, thermo-active geostructures meanwhile also result in larger activated volumes (efficiency). Furthermore, the high thermal conductivity and heat storage capacity of concrete compared to soil or air have a positive effect on energy exchange (thermal properties). Finally, the concrete cover provides excellent protection of the heat exchanger pipes against damage, which means that failures can only occur in the course of installation, these being extremely rare (robustness) (Brandl 2016). In tunnel and thus also in metro construction, energy non-woven geotextiles, energy anchors (Brandl 2006), energy lining segments (Frodl et al. 2010) and energy sheet piles (Koppmann 2021) can be used in addition to the systems already mentioned (Adam & Markiewicz 2009; 2010; Bourne-Webb & Gonçalves 2016).

Infrastructure buildings, and thus also metro stations, are particularly suitable for geothermal energy utilization by means of thermo-active geostructures due to the relatively constant energy demand on the one hand (discussed in chapter 2.3) and on the other hand due to the structural components that are necessary anyway in great depths with seasonally constant temperature conditions (Brandl 2016). In addition, the slightly higher construction costs and at the same time lower operating costs due to the long service life of infrastructure lead to the expectation of a short payback period of the costs. In addition to the economic reasons, however, there are also arguments for the use of geothermal energy in public buildings dealing with social aspects. Such flagship projects can create awareness of energy efficiency and the promotion of sustainable energy sources (Camacho Ballesta et al. 2022) and thus "set a good example".

Most projects with energy geostructures have been realized in Austria, Switzerland, Germany, and the UK (Salciarini et al. 2026). The technology is also becoming increasingly important in China, although there is only little documented information on the actual extent and functionality of comparable geothermal systems in infrastructure buildings (Laloui & Rotta Loria 2019). The Institute of Geotechnics at the TU Wien has been working on the topic of geothermal energy utilization by means of energy geostructures for more than three decades. This concerns basic research (Adam & Markiewicz 2002a; Markiewicz 2004; Brandl 2006), numerical modeling (Adam & Markiewicz 2002b; Markiewicz 2004), application-oriented research (Adam & Markiewicz 2003; 2009; Markiewicz 2004; Brandl et al. 2010; Brandl 2016; ÖBV 2019) and large-scale experiments (Markiewicz & Adam 2020). The project discussed in this paper was supervised by members of the institute already in the planning phase in the early 2000s, feasibility studies (TU Wien & Planungsgemeinschaft U2/2 Taborstraße 2001; 2001) were carried out, the geothermal system was designed, the measurement concept was developed, and the installation of the sensors was accompanied (Markiewicz 2004). The Institute of Geotechnics at TU Wien is also responsible for the recording and evaluation of both measurement phases, the one from 2008 to 2011 and the one since 2020.

1.2 SCIENTIFIC RELEVANCE AND STATE-OF-THE-ART ON THE THERMO-MECHANICAL BEHAVIOR OF ENERGY WALLS

While an increasing number of scientific papers on the thermo-mechanical behavior of energy piles based on large-scale tests, laboratory experiments and numerical modeling have been published in the last two decades (a comprehensive listing was made, for example, by Cunha & Bourne-Webb (2022)), comparable studies on energy diaphragm walls are hardly available (for existing examples see (Di Donna et al. 2017; Dai et al. 2023)). This circumstance is due to the additional complexity involved combined with less widespread use and a very costly large-scale test execution. Considerations regarding the expansion and deformation behavior of energy diaphragm walls are comparable to those of energy piles (as foundation elements), but in this project they are subject to the following additional complex boundary conditions:

- The bottom slab and (intermediate) ceilings serve as bracing elements and, together with the complete shaft structures with a comparatively complex ground plan geometry, result in a highly statically indeterminate, mutually influencing three-dimensional system in which the stiffness distributions are complex (complex structural geometry).

- Due to earth and water pressure, the diaphragm walls of the metro station examined here are mainly loaded horizontally and thus as slabs. They bear comparatively small vertical loads as walls due to the lack of a superstructure over the station (complex mechanical loading).
- Due to the large activated area, the temperature load is applied by a large number of heat exchanger circuits, whereby information on the flow rates and temperature distributions is unknown or is only known at certain points. In addition, the wall elements are usually only surrounded by the ground on both sides in the lower area (below the bottom slab), while most of the wall features a ground and air side with each having different boundary conditions (complex thermal loading).
- Individual wall elements (unlike individual piles) cannot be considered decoupled even with otherwise known boundary conditions, since the system deforms as a whole despite a possibly locally limited temperature change (complex thermo-mechanical coupling).

Due to the aforementioned challenges, the studies on energy walls documented in the literature mostly rely on numerical modeling, with possible validation by sparsely available measurement data (see, for example, (Bourne-Webb et al. 2016; Coletto & Sterpi 2016; Di Donna et al. 2021)). Results indicate that the air side (and associated heat transfer mechanism by convection) present in energy walls, as opposed to energy piles (as a foundation element), has a strong impact on system performance (Bourne-Webb et al. 2016). This can be advantageous. For example, if station heating occurs due to waste heat generated by trains and passengers, as has been documented for example in London (Botelle et al. 2010), this could result in an additional energy gain (Di Donna et al. 2017). However, if there is no corresponding heating demand (e.g., in the case of pure cooling demand), this heat generation has a negative effect on the temperature level of the heat exchanger elements. Previous studies have also shown that seasonal air temperature fluctuations have a greater effect on the temperatures of the energy walls than the heat exchanger operation itself (Bourne-Webb et al. 2016). On the other hand, energy diaphragm walls, for example in (Sterpi et al. 2017), are attested to have quite relevant additional normal forces and bending moments as a result of thermal operation on the basis of numerical investigations, and which would have to be taken into account in the design.

In order to validate the findings of numerical models on energy walls or energy bottom slabs for infrastructures, actual measurement data are indispensable. In addition to the Lainzer Tunnel, Taborstraße metro station represents the second infrastructure project monitored by TU Wien. In the course of the world's first large-scale application of thermo-active geostructures in metro stations (Brandl 2006), an energy diaphragm wall element of the Taborstraße station was equipped with numerous measuring instruments. The construction and early measurements have been presented in (Markiewicz 2004; Brandl 2006; 2016; Adam & Markiewicz 2009; Laloui & Rotta Loria 2019), among others. More recently, comparative assessments of design predictions and long-term operational performance have been presented, addressing the energy performance and thermo-mechanical response of an instrumented energy diaphragm wall segment based on monitoring data up to early 2022 ((Brunner et al. 2022), in German; (Adam et al. 2023), in English). The present paper again provides an overview of the station and subsequently focuses on its energy performance, comparing the predicted energy demand with the measured energy use based on an updated dataset covering the periods from 2012 to 2014 and from December 2020 to early 2026. For an evaluation of the temperature and strain data of the instrumented energy diaphragm wall element, reference is made to (Brunner et al. 2022) and (Adam et al. 2023).

2. TABORSTRAẞE METRO STATION

2.1 PROJECT DEVELOPMENT OF THE GEOTHERMAL PLANT

In 2001 and 2002 respectively, the builder and operator of the Vienna public transport network, Wiener Linien GmbH & Co KG, commissioned the Institute of Geotechnics of TU Wien, which at that time had already been involved in the research and development of geothermal systems, to prepare technical feasibility studies for geothermal systems (TU Wien & iC Consulenten 2002; 2002). Four of the new metro stations of the U2 line to be extended at that time – U2/1 Schottenring, U2/2 Taborstraße, U2/3 Praterstern and U2/4 Messe-Prater – were then selected with the aim of covering their future heating and cooling needs largely with geothermal energy.

The entire Taborstraße station consists of two shaft structures and two tunnel tubes connected by cross passages. The station building was constructed using the top-down method, with the Taborstraße shaft energy diaphragm walls constructed in 2003 and the energy bottom slab constructed in 2004. Additionally, heat exchanger pipes were also installed in piles and parts of the station tunnel inverts (Brandl et al. 2010).

Figure 1 shows photos of the construction site, with part (a) showing the lower part of the instrumented diaphragm wall (element No. 18) covered with heat exchanger pipes and part (b) showing the installation of this reinforcement cage into the slurry trench. Part (c) shows the connection lines to the energy diaphragm walls as well as one of the three penetration locations through the future 2m thick bottom slab. Part (d) shows the connection point of heat exchanger circuit No. 2 of diaphragm wall No. 18, the cables of the installed sensors, and the temperature sensors attached to the supply and return lines. The station was opened in May 2008. Figure 2a shows the ground plan of the shaft structure. The respective positions of the two cross sections A-A and B-B, shown in Figure 2b and Figure 2c–d respectively, are indicated in the floor plan (Figure 2a).

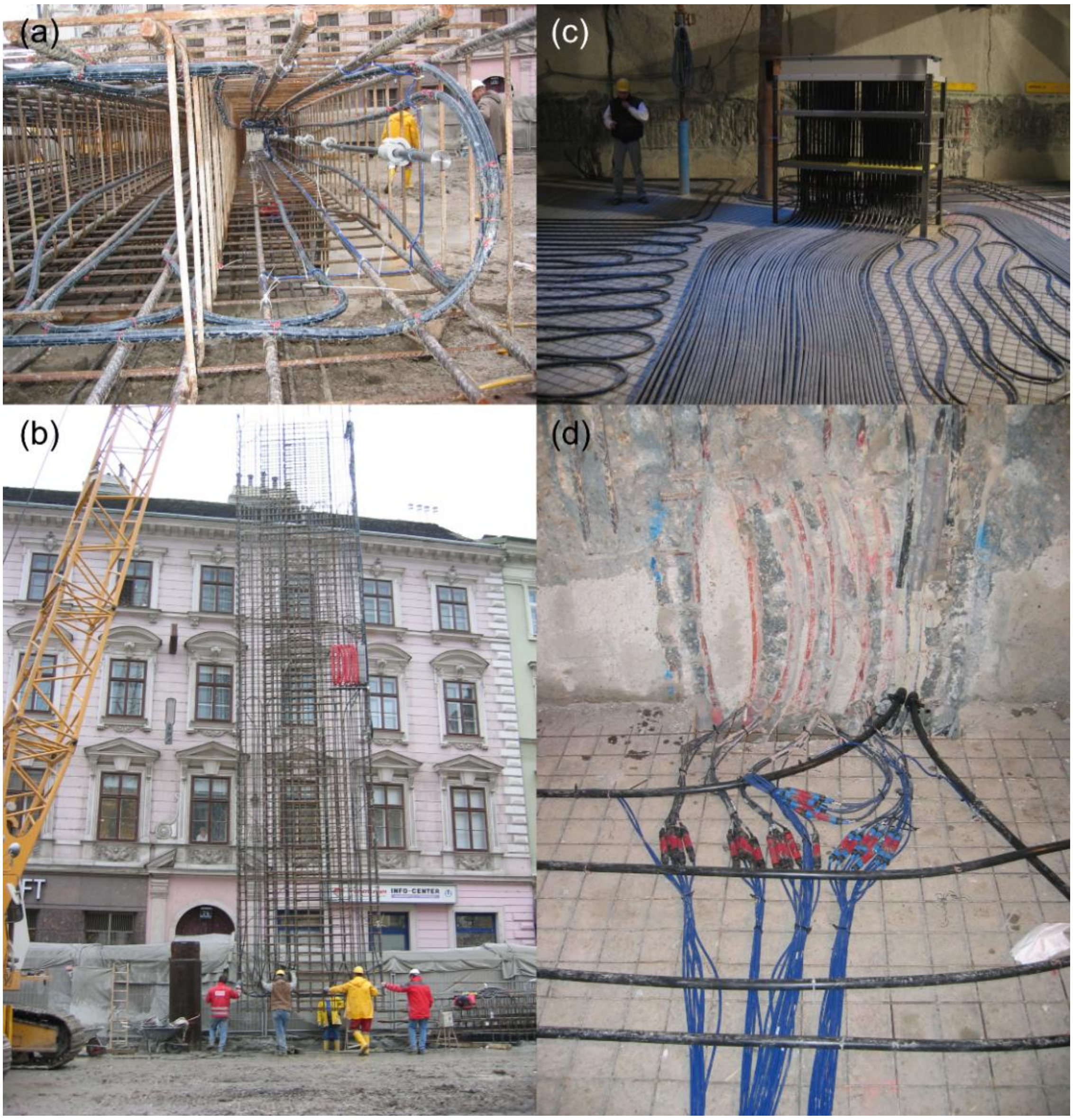

Figure 1: Installation and instrumentation at Taborstraße station: (a) Lower reinforcement cage of diaphragm wall No. 18 with offset sensors to clear the tremie pipe; (b) Lifting of the cage, showing protective covers for pipe and cable connections; (c) Heat exchanger pipes and feed-throughs beneath the 2 m thick bottom slab; (d) Inlet/outlet configuration, including attached temperature sensors and sensor cables.

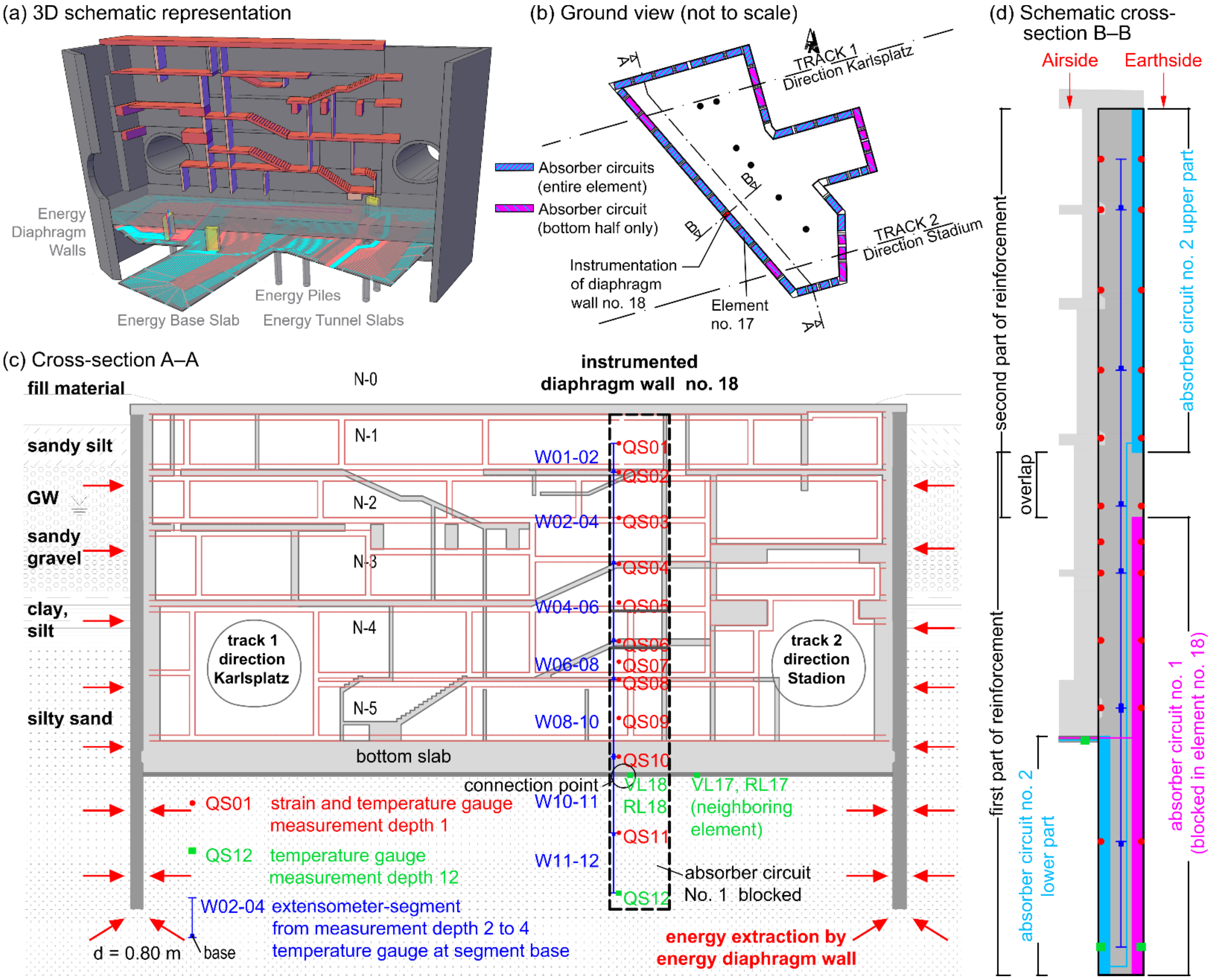

Figure 2: (a) 3D schematic representation of the thermally activated components; (b) Ground view of the metro station Taborstraße section T with position of instrumented diaphragm wall No. 18, neighboring element No. 17 and marked cross sections A-A and B-B; (c) Cross section A-A of U2 metro station Taborstraße section T with ground profile, position of instrumented diaphragm wall No. 18; (d) Schematic illustration of cross section B-B showing the installed heat exchanger circuit's positions (No. 18).

The majority of diaphragm wall elements are equipped with two geothermal heat exchanger circuits extending over the entire element height. Those elements that were penetrated by either the tunnels or the staircase are only partially equipped.

The connection of a total of over one hundred heat exchanger circuits (Enercret 2009) to the individual diaphragm wall elements is made below the bottom slab (see Figure 1c and d), which is also fully thermally activated. The design principle followed was to limit the length of the individual heat exchanger circuits, on the one hand, to limit pipe friction losses and, on the other hand, to install them at approximately the same length to ensure largely uniform flow behavior (TU Wien & Planungsgemeinschaft U2/2 Taborstraße 2001).

The quite critical penetration of the heat exchanger circuits into the interior of the structure (ÖBV 2019) due to the high groundwater pressure takes place through the base slab at three points, where the distributors T1 to T3 are ultimately also arranged (Figure 2a). Subsequently, collector pipes lead to two heat pumps and two cooling machines respectively. The heat exchanger pipes in the thermo-active geostructures, as well as the connecting pipes to the distributors together with the manifolds, form the so-called primary circuit (Wiener Linien 2007).

2.2 PREDICTED ENERGY DEMAND (DESIGN PHASE)

In a feasibility study (TU Wien & Planungsgemeinschaft U2/2 Taborstraße 2001), various systems for geothermal energy utilization were investigated at an early design stage in order to be able to discover the heating and cooling requirements of the station monitoring rooms, transformer and switch rooms, storerooms, etc. The feasibility study also examined the provision of energy for neighboring buildings, but this was not implemented. In the course of the execution design, more detailed considerations were given to the selection of thermally usable components, the arrangement of the distribution locations, and the relevant pipe routing. Finally, energy diaphragm walls with a developed area of 2300 m^2 and an energy bottom slab with an activated area of 1700 m^2 were realized at the U2 station Taborstraße. In addition, an area of 281 m^2 was thermally activated by energy piles and parts of the station tunnels were also equipped with heat exchangers in the invert area (Brandl et al. 2010). A total of 108 heat exchanger circuits with a total length of 26,431 m were installed.

The system was initially sized based on the projected thermal demands of the station, as estimated during the design phase (Markiewicz 2004; Brandl 2006):

- Max. thermal heating power 95 kW
- Max. thermal cooling power 67 kW
- Annual heating energy 175 MWh/a
- Annual cooling energy 437 MWh/a

However, following the completion of the project, Brandl et al. (2010) reported the actual installed capacity of the energy geostructures. These figures represent the maximum usable output of the system (after heat pumps and cooling machines) as built, which exceeded the initial design requirements:

- Max. thermal heating power 185 kW
- Max. thermal cooling power 114 kW
- Annual heating energy 175 MWh/a
- Annual cooling energy 525 MWh/a

These numbers represent the usable energy quantities in each case. The heat exchanger load decreases for heating and increases for cooling by their share of electrical energy. This is due to the fact that the shares of the required external energy influence the energy actually used in the secondary circuit (on the user side), as shown in Figure 3. Consequently, in the primary circuit, the heat exchanger load is reduced in the heating demand, while the load is increased in the cooling mode. If there is both heating and cooling demand at the same time, the actual heat exchanger load results from the difference between the heating and cooling energy (Markiewicz 2004).

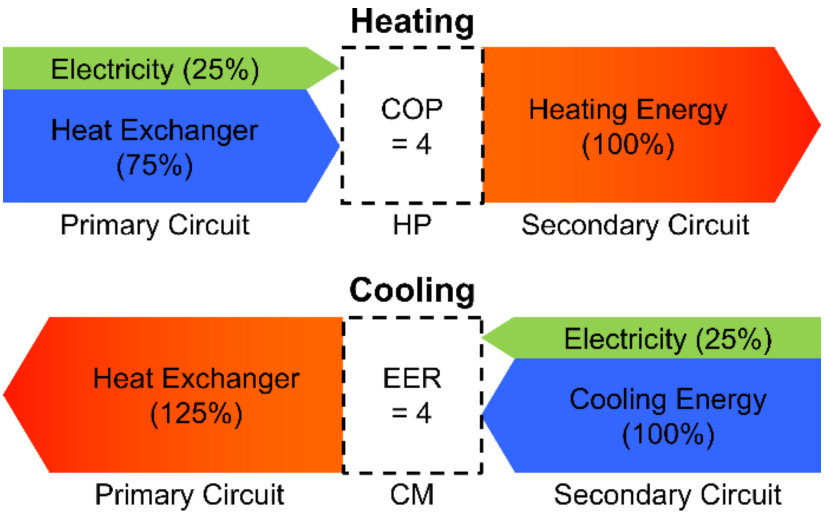

Figure 3: Schematic energy flow for heating and cooling. The coefficient of performance COP and energy efficiency ratio EER characterize the efficiency of the heat pumps and cooling machines, respectively.

2.3 MEASURED ENERGY DATA (OPERATIONAL PHASE)

Between October 2008 and July 2010, the energy data of the system was recorded on the first day of each month (Mauritz et al. 2010), and since December 2020, approximately monthly. This data is shown in Figure 4 based on the heating and cooling energy used in the secondary circuit, i.e., after the heat pumps and cooling machines respectively. In addition, the electrical energy required to operate the heat pumps, cooling machines, and circulators is also shown. Figure 4 shows that the heating energy used exceeds the cooling energy by a factor of about two. However, the external electrical energy supplied to the heat pumps or cooling machines is about the same. This can be attributed to the fact that the external energy is not usable in the case of cooling as well as differences in performances (COP resp. EER, Figure 3).

In this project, the existing energy measurement data can be compared with the predicted energy quantities, as shown in Figure 5. This figure incorporates the design-phase estimates previously detailed (Markiewicz 2004) as a baseline for the monthly energy demand, plotted against the actually measured heating and cooling energy consumption. Since the heating and cooling energy measurements resumed in December 2020 are taken on different days of the month, these measured data are attributed to the individual months by linear interpolation.

The data collected from December 2020 and onwards start in a similar order of magnitude to those in the first monitoring period from October 2008 to July 2010. Apart from a single peak in heating energy used in December 2009, heating energy reaches monthly peaks between 20 MWh and 27 MWh. Accordingly, the peak consumption of heating energy usually occurs in December or January. A pronounced reduction in heating energy consumption occurred during the 2022/23 heating season, primarily due to the sharp rise in gas and electricity prices after the Russian invasion of Ukraine in February 2022 and the resulting energy-saving measures. Although consumption increased in subsequent years, it remained significantly below the levels of the initial monitoring periods.

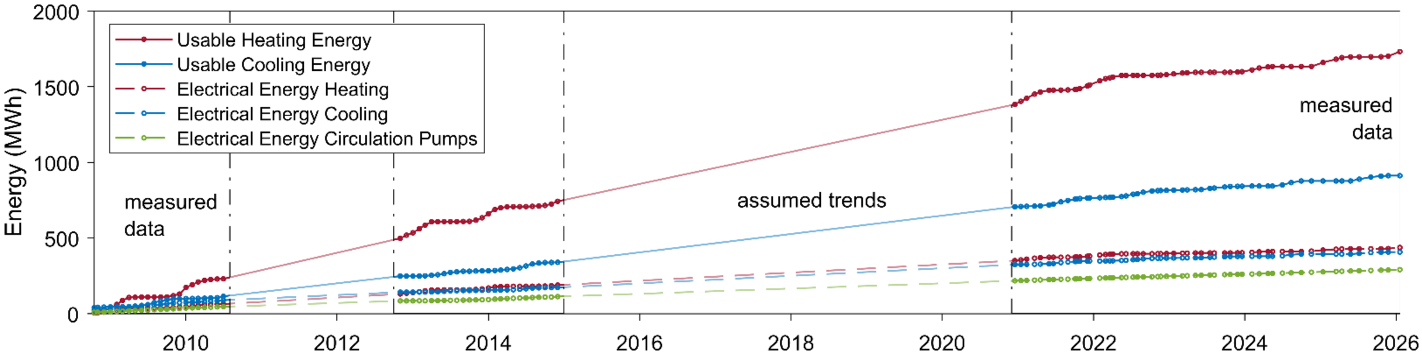

Figure 4: Used heating and cooling energy (secondary circle) and external electric energy for heat pumps, cooling machines, and circulation pumps.

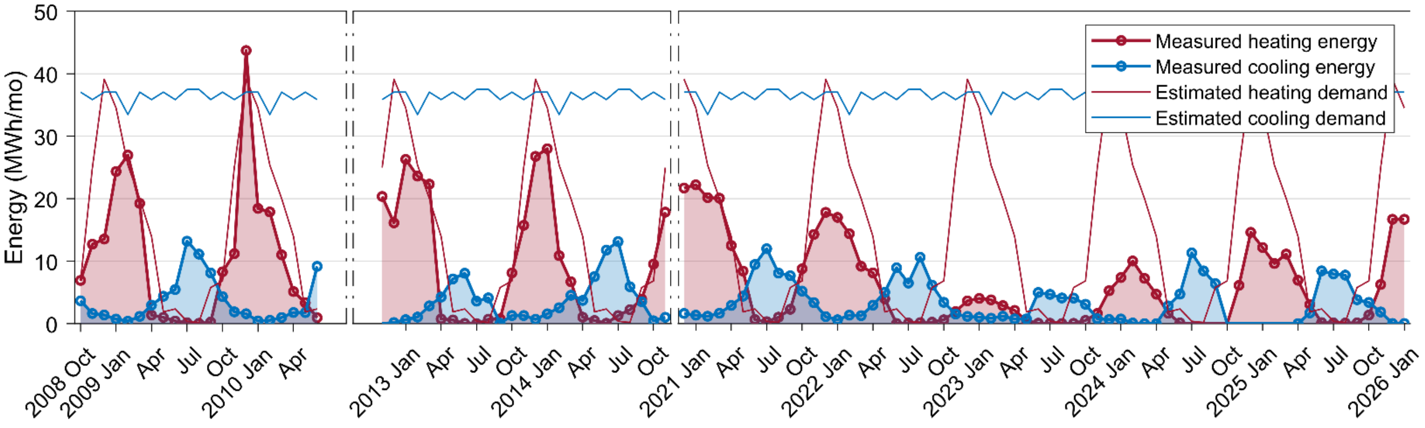

Figure 5: Comparison of predicted monthly energy demand (based on design-phase estimates) and actually measured heating and cooling energy.

An annual cycle can be chosen as a basis for a comparison of the predicted and measured energy quantities. In this case, for example, the year 2009 is suitable since a complete series of measurements is available. However, it is noticeable that – as already described – in December 2009 a comparatively high amount of used heating energy was recorded compared to the other years. Since the reason for this is unclear (possibly due to the installed staircase heating (Wiener Linien 2007), which was only operated in the first few years), the period December 2008 to November 2009 is chosen as the basis for the following observations.

In the observation period described, the cumulative annual heating energy is 106 MWh. In 2021, i.e., about 10 years later, the cumulative annual heating energy is 129 MWh. The potential of the thermo-active geostructural system of 175 MWh has thus not yet been exploited, so that there are reserves. This observation is also evident from the temperature data presented elsewhere (Brunner et al. 2022; Adam et al. 2023). With regard to cooling, the measured data show that in 2009 the annual cooling demand was 55 MWh and in 2021 it was similar at 58 MWh. Compared to the design value of 437 MWh, this shows that there are still larger reserves. In the design phase, a continuous cooling demand over the entire year was assumed. In contrast, however, the measured data show a seasonal fluctuation, with the cooling demand reaching its maximum in July and its minimum in February. In the design phase, it was also assumed that the cooling demand would increase slowly over the course of the first few years (warming of the structure) and that the design case would only be reached after a few years. However, a comparison of the measured data from the first years with the most recent measured data shows that the cooling demand has not increased significantly since the beginning of monitoring.

3. CONCLUSION

Although thermally utilized diaphragm walls and bored pile walls have been increasingly used in recent years, few case studies exist on their everyday energy performance. This is due to the complex boundary conditions and the fact that large-scale field tests are very costly. However, the use of these thermo-active geostructures for heating and cooling buildings has enormous potential as a locally obtained and used renewable primary energy source. The Wiener Linien GmbH & Co KG have done international pioneer work with their decision in the early 2000s to supply several metro stations with geothermal energy and to use the structural concrete components, which were necessary anyway for the station structure, as geothermal heat exchangers to cover the heating and cooling demand. Due to the scientific support of the Institute of Geotechnics of TU Wien and the first instrumentation of a thermally activated diaphragm wall element, it has been possible to generate hitherto unique long-term measurement data of the temperature and strain curve of an energy diaphragm wall.

This paper highlights the scientific relevance of the existing and ongoing measurement data of the instrumented energy diaphragm wall in the U2 station Taborstraße. It gives an overview of the project development of geothermal usage at the station, and it contains a first presentation and interpretation of the existing measurement data. The most recent heating and cooling energy data of the entire station collected since December 2020 show a recently reduced heating energy demand compared to the energy demand of the years 2008 to 2010 after the opening of the station. This results from energy-saving measures introduced in response to rising energy prices since summer 2022. While the prognosis of average annual heating energy carried out in the design phase was almost fulfilled in early years, the actual annual cooling energy required is constantly far lower. Thus, there are still large system reserves, especially for the cooling operation. The results offer insights for any dimensioning or assessment of similar systems in the future.

4. ACKNOWLEDGEMENTS

It is greatly appreciated that the Wiener Linien GmbH & Co KG have done international pioneer work with their decision in the early 2000s to supply several metro stations with geothermal energy and to use concrete structures as geothermal heat exchangers to cover the heating and cooling demands.

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Prof. Dr. Dietmar Adam
TU Wien, Institute of Geotechnics
dietmar.adam@tuwien.ac.at

Dr. Roman Markiewicz
TU Wien, Institute of Geotechnics
roman.markiewicz@tuwien.ac.at

Dipl.-Ing. Adrian Thylbert Brunner
TU Wien, Institute of Geotechnics
adrian.brunner@tuwien.ac.at