E3S Web of Conferences 172, 16008 (2020) http://doi.org/10.1051/e3sconf/202017216008
NSB 2020

Underground parking lot at Turku market square - Zero energy parking hall and the biggest solar energy storage in the world

Rauli Lautkankare[1] *, *Nikolas* Salomaa[2], *Birgitta* Martinkauppi[3] and *Anna* Slobodenyuk[1]

[1]Turku University of Applied Sciences, Joukahaisenkatu 3, 20520 Turku, Finland
[2]NollaE ltd, Lemminkäisenkatu 12, 20520 Turku, Finland
[3]University of Vaasa, Wolffintie 34, 65200 Vaasa, Finland

Abstract. This paper opens the case Turku market square underground parking lot from the energy perspective. Also constructional and historical aspects are presented. Heavily populated city center has faced several challenges, such as intense traffic. Uncomfortable local tailpipe emissions and lack of parking spaces have decreased living conditions for the citizens and visitors. Therefore, total renovation of main market square of Turku was started in autumn 2018. Together with that, municipality should respond not only to primary needs, but also to national and global environmental targets. One of the new strategy objectives for Turku is being carbon-neutral city by 2029. Hence, project was based on large-scale renewable resources utilization for urban underground spaces. Research and analysis of possible technical solutions was made. Modern time is characterized by climate change and strong measures that need to be taken to stop the global warming. The heat, cold and electricity should be produced in a carbon neutral manner. This doesn't exclude heated multilevel car parking facilities either. As the parking capacity grows and finding a free place is easier, a positive environmental effect is expected to be reached. The described underground parking lot in Turku is first of its kind in many ways: 1) Never before underground parking lot has dug up and constructed into clay-based soils in Finland, 2) it is probably the first zero carbon energy parking hall in Europe and 3) it has the biggest solar thermal energy storage in the world.

1 Introduction

Zero-energy buildings are modern trend in construction industry worldwide. Energy supply of such buildings are fully based on renewable sources. Highly energy efficient construction is desired development strategy for city of Turku, Finland. Together with that, lower emission level from zero-energy concept could make a positive impact into national environment and well-being.

A particular challenge relating to low-carbon heating and cooling is the mismatch between supply and demand. Significant daily and seasonal variations in heating and cooling demand are interconnected by daily and seasonal variations in the supply of energy from renewable sources. This results in a need for inter-seasonal energy storage in northern regions.

Systems where solar energy is stored underground can be efficiently used for district water and space heating in Finland [1]. Rehman & al. stress the importance of system configuration and main component sizing. Former studies have highlighted that storing heat in clay can be cost-effective solution for heat storage [2, 3]. However, heat increases the consolidation and creep together with decreasing the shear strength of clays [2]. This arises the risk for settlement and may jeopardize the stability of clay.

Market square of Turku associated with city centre by both locals and visitors. The place is surrounded by four main streets: Aurakatu, Eerikinkatu, Kauppiaskatu and Yliopistonkatu and it is square-shaped area with sides 120 per 120 meters. General plan of Turku city was developed by architect Karl Ludwig Engel, who introduced square as a multipurpose area. Together with commercial purposes, square was implied as public fire-escape zone.

Nowadays market square is also a multipurpose area. Shopping centres, public transportation areas, restaurants, cafes, offices, banks and hotels every day attract several thousand people. About 22000 times passengers enter bus in market square area daily [4].

The general trend since the beginning of automotive industry is an increasing number of cars around the world, which requires more parking space. Only in Turku number of registered in traffic passenger vehicles reached 79 thousand cars (year 2018) [5]. The parking areas in many urban cities have limited availability when compared the number of cars. Urban land areas are in some places minimal or not available at all. This has caused increase in construction of urban underground spaces (UUS) which urban underground parking (UUP)

* Corresponding author: rauli.lautkankare@turkuamk.fi

also belongs. The prices of urban land may be so high, that it provides a justification for UUS.

Sustainability is an important issue for UUS [6-9]. The sustainability includes natural benefits provided by the underground like excavated material (e.g. sand, rock), drinking water and ground water supply, cultural heritage [6]. The resource potential of underground thus needs to be evaluated [10, 8]. Qiao et al. 2019 evaluated potential threats for it like changes in geothermal energy or ground water due to new underground conditions. Limited underground space can also cause a conflict between different usages like geothermal use and transport use [11]. This is not the case with Turku Parking lot (also called as Toriparkki referring to its Finnish name). The parking lot is constructed under Turku town square and it uses geothermal energy combined with solar storage to provide its heating. The groundwater and cultural heritage related aspects were taken into account in design phase.

The other aspect of underground parking is need for equipment and energy. Matshushita et al. [12] made a comparison between aboveground and underground parking lots and found that underground lots had higher equipment loads and energy consumption. Underground car parks need naturally ventilation, which increase need of energy. Ventilation is needed to guarantee air quality, remove air contaminants (especially carbon monoxide) and in some countries, to keep air temperature in suitable range [13]. The cars entering and leaving car parks cause emissions (e.g. carbon oxides, hydrocarbon and nitrogen oxides) and increase inside temperature due heat generated by the cars both of which are dependent on operating time of car engine and number of cars [14]. Ventilation naturally removes part of the generated heat. In many part of the world UUPs do not need heating and in fact, the heat need to be specially ventilated out. This is not case in Finland. UUPs in Finland do typically need heating.

A typical aspect for reducing carbon emissions from parking garages is to use solar power systems like photovoltaics (PV). PV is employed to produce electricity e.g. for charging cars [15], or energy efficiency [16, 17]. Many parking garages / halls do not necessary need heating because of their location is in a warm climate. This is why there is not so many studies specifically on parking garages utilizing thermal storage. One study, which suggest using existing earth-contact concrete elements for heating parking garage has been made by Brandl [18].

Toriparkki project consist of multiple constructions:

- Parking lot,
- Underground shopping centre and
- Market square buildings

Visualizations made by architects show how the market square will look like after the Toriparkki and all the connecting construction works are completed (Figure 1-3).

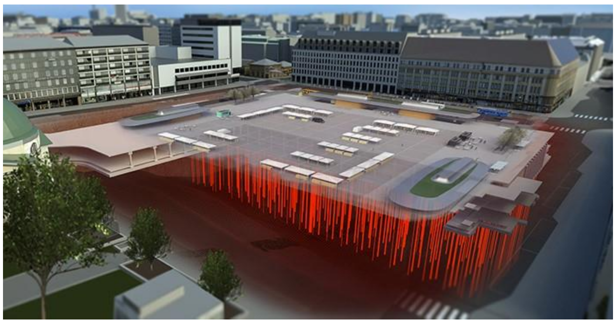

Fig. 1. Market square facilities model. Supporting piles shown red.

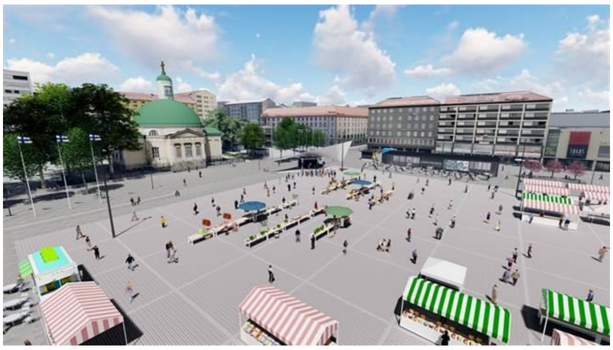

Fig. 2. 3D-model of market square, view from south corner.

Fig. 3. 3D-model of market square pavilion building. https://www.turku.fi/turun-uusi-kauppatori.

Purpose of the market square project is important for the city to rebuild old city centre. The city of Turku wanted to bring a modern and unique look of market square. Eventually a group of specialists had an opportunity to perform a futuristic construction and combine it with functionality.

The most important aspects of development for Finland is sustainable, environment-friendly and economically beneficial growth. Main goals for Turku city include:

- Profitable land-use development attractive for investment,
- Reaching carbon neutrality by 2029,
- Actively optimizing regional transport and energy solutions,
- Carbon neutral circular economy as one of Turku top industrial policy themes. [19]

In Turku, the heating of UUP is planned with solar energy storage which has been constructed with energy piles. Energy piles have been already utilized in many places and shown to be a proper solution for heating, e.g. airport [20] or air conditioning [21]. The geothermal energy and solar storage make Turku UUP zero energy parking lot. Although there have been some studies [22], which considers renewable energy with underground parking. According to authors' knowledge, Turku has the first zero energy UUP.

2 Project task description

This paper presents case Turun Toriparkki, its historical, environmental and constructional relations, and energy solutions. Additional literature review regarding urban underground spaces is presented.

City centres often have dramatical environmental problems. Central location of services attract people from near and far and transportation causes local air pollution. Market square is an important transportation point for the entire public transport. Together with public transport, private car drivers are regularly looking for the parking places. During the search, cars are typically moving quite slowly. That intensifies tailpipe emissions, disturb traffic and increase probability for accidents related to bypassing cars.

Turun Toriparkki can solve some of these problems by offering more parking space and at wintertime keeping cars warm, which reduces emissions as mentioned earlier.

Turun Toriparkki is a facility that can be categorized as an urban underground parking. Together with underground parking this project includes marketplace and shopping mall. Total construction area equals 30810 m^2. As referring to its energy system, Toriparkki is a borehole thermal energy storage (BTES) system.

2.1 Borehole Thermal energy storages

Borehole thermal energy storage (BTES) is a seasonal storage of thermal energy for long periods - up to several months. BTES is one type of seasonal thermal energy storages (STES) that enable heat or cold to be stored. Storages have an important role in a smart energy system where sector coupling and interconnected systems can provide demand flexibility and synergies.

Locations suitable for BTES installation supposed to have suitable geological properties. Construction require drilling deep openings in bedrock and back-filling with specific materials heat exchanging properties, such as high conductivity.

Toriparkki consists of energy piles that are considered as BTES system as a several piles form a field of holes into the ground. This field is called energy well field or shortly energy field. Usually energy fields are positioned close to building not under the building. All the time under the building solutions are coming more and more common as piles supporting the building can be utilized for energy purposes too [23].

Latest studies [24] on thermal energy storages proved that financially profitable BTES installations should have quite large volumes (starting from 20 000 m^2). This technology has already been implemented around the world since decades ago [25], including countries with similar climate and geology conditions (Sweden, Northern Germany). Local conditions, such as soil freezing, was a limiting factor for few technical options. Apart of that, presence of four seasons in Finland supported improved energy efficiency for BTES systems. Ability to load thermal capacities during summer and unload storage during winter (when heating is required) is a desired task for those heat storages.

There are wide scale of possibilities in BTES systems. Some installations require drilling shallow boreholes from 30 to 100 m deep. In the other cases, deep heat from 1 to 3 km is desired [26]. Solar collectors are typically used as a source of thermal energy [27, 28]. However, energy provided by sun in some cases is limited, so multiple sources were also studied [29]. Therefore, heat pumps are suitable for up-scaling and refining heat from several sources and for distinguished purposes.

One of the main disadvantages of underground seasonal storages like BTES is heat loss to the surroundings. Two major local ground qualities that affect the storage efficiency and the losses from BTES are the thermal conductivity and the groundwater level and its movements. [1]

Finland is located in the Fennoscandia Shield and the ground properties are suitable for BTES [30]. In Finland the mean thermal conductivity of rocks is 3.24 ± 1.00 W/m·K [31]. In addition, the groundwater level plays an important role in thermal conductivity [30]. The groundwater level in Finland is usually located at a depth of 1–4 meters below the surface, however, it can be located as deep as 20 meters in ridges and bedrock [32]. Most of the Finnish bedrock is unbroken and has little or no groundwater flow [30, 32]. The size of the borehole storage is also important for heat loss. Vertical borehole lengths are usually in the range of 30–100 m with approximately 3–4 m separation [33]. The borehole depths in recent installations have gone as deep as 200 m [34]. The cylindrical shape of the storage reduces the losses [30]. In addition, the big volume reduces relatively heat losses.

2.2 Climate and soil properties in-situ

City of Turku is located in the southwest coast of Finland, in the region of Proper Finland (Varsinais-Suomi). The region was originally called Suomi (Finland), later it became the name for the whole country. Turku is the sixth largest town and the third largest urban area in Finland after the Greater Helsinki area and Tampere sub-region (479,694 inhabitants) [5].

Local climate is a mixture of coastal and inland climate types. Finnish Meteorological Institute confirms typical snow season start in 6.11. and lasts up to 10.4. which gives in total 85-150 days. Normally temperatures for winter period could vary dramatically during the day and snow melting or soil icing occurs regularly.

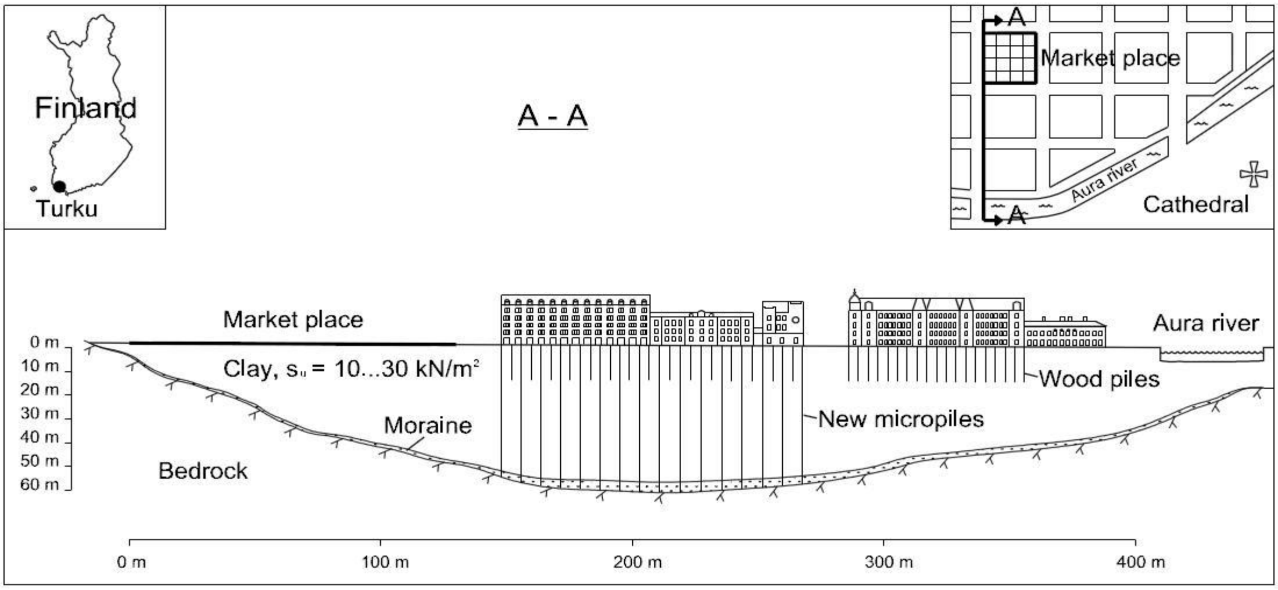

Fig. 4. Clay layer distribution from market square to Aura River.

Geotechnical studies made around the Toriparkki by geoengineering consult Maanpää [35] states that soil consist of 1,5 m dry clay layer and underlying 20 m of wet clay. Bedrock consists of plutonic and metamorphic rocks, including granites, gneisses and amphibolites [36]. Glacial and postglacial sediments cover bedrock layer [37]. Clay is dominating in Turku, it covers up to 50-60 % of the land area [38]. Glacial clays with mean water content 70 %, also presented locally [39].

Figure 4 illustrates clay layer distribution in market square. On the northern side the clay layer is appr. 5 meters thick. It gets thicker towards south and reaches 50 meters in the southern side. [40]

2.3 Soils for storage purposes

As the construction site lies on the clay, energy piles are suitable for thermal storing. On the other sites, bedrock is convenient for borehole systems. If the site has sand or other permeable soils, storing could be challenging. Aquifer thermal energy storage (ATES) could be possible in that case. In Finland, only one ATES is operating [41]. For instance, there are almost 3000 ATES systems in Netherlands [42] and nearly 200 in Sweden [43].

All the buildings around the market square have gone through an underpinning project during last decades. Old wooden cohesion piles have suffered from the sink/lowering of groundwater level. For that reason, aerobiological bacteria were able to cause deterioration into the top of the piles. Nowadays all the buildings have tubular steel piles supporting them. Variety of underpinning methods and impacts has been studied in these city center buildings [40].

Tubular steel pile is perfect for injection-extraction of heat due to the hollow section shape it has - similar as a borehole. Steel is also a good material for energy transmission as it has high thermal conductivity. Underpinnings have always been implemented using tubular steel piles in vicinity of market square. In none of the cases, piles were used for energetic purposes even though it was considered in Turku at 2012-2014. That case (Property ltd Turun Ilmarinhovi) would have been the first to pilot energy piles – or actually hybrid energy piles - in underpinning project [44]. Timing was not favourable. Underpinning had to be made without any energy functions included.

Today, several BTES projects are on the planning table in Turku area and South-West Finland. Just to mention few, these include energy pile projects in Kupittaa campus building, in Skanssi multi-storey residential building and in Kaarina small-house and commercial building. In these positions, soil consists from six to 18 meters of clay. Toriparkki is the biggest in this energy pile BTES category.

Additionally, deep heat BTES project announcements such as utilizing waste heat and thermal storing can be noticed more often in media news. One of the biggest deep heat projects will start at 2020 in Korvenmäki, Salo. Six boreholes will reach the depth of three kilometres. Project got national funding up to three million euros. The system will support district heating eventually, and it will reduce significantly CO_2 emissions as energy from deep holes replace the use of oil during peak demand. [45]

3 Solutions and results

Turku market square is an important project for the region. It is a multipurpose construction. Highly educated specialists including architects and engineers combined their forces to deliver this futuristic square. Among functionality, there was a remarkable amount of technical problems solved. Building planned as energy efficient and environmentally friendly parking space for 600 cars. This project would solve one important issue with air pollution in the city centre. Additionally, there would be installed useful solution for walking people - de-icing surface feature. All these together were fulfilling targets from municipality and its development plan. Finding an appropriate combination of innovative solution was implement using NollaE optimization tools.

With the developed model and control strategy, the long-term thermal performance of the system was simulated. The specific parameters used in the simulation is given in Table.1

Table 1. Parameter setting.

Item	Unit	Value
Collector area	m2	23250
Flowrate at collection loop	l/s	105
Collector efficiency	no commercial collectors	
Heat conductivity of grout	W/(m*K)	2,2
Heat conductivity of soil	W/(m*K)	1,6
Heat conductivity of pipe wall	W/(m*K)	0,544
Outer diameter of tube	mm	40
Inner diameter of tube	mm	35,6
Inner diameter of the energy pile	m	0,12
Initial soil temperature	ºC	9,2
Volumetric heat capacity of the soil	kJ/m^3*k	3600
Total flowrate in the GHE	l/s	119
Length of heat storage season	h	4440
Length of heat extraction season	h	4320
Supplying temperature of collector system	ºC	60
Returning temp. of heating network	ºC	10
Feasible outlet temp. deviation	ºC	15
Number of energy piles	pcs	561
Length of the energy piles	m	35
Number of partitions	pcs	72
Number of subzones in each partition	pcs	11

The parameters shown in Table 1 are specific for this project. They are collected from the technical drawings of the building and ground tests performed on site.

Toriparkki has more than 2000 piles as a supporting structure. 561 of them are energy piles. Pile length varies mainly from 15 to 45 m, at some point even 55 m. Piles used are tubular steel piles, D = 140 or 170 mm, material thickness 10 mm (pile specification RR140/10 or RR170/10). Energy piles have special filling inside in order to optimize thermal conductivity. In addition, energy piles have collector pipes inside and those pipes have water inside as heat-exchanger liquid. Usually heat-exchanger liquid contains bioethanol or glycol to prevent liquid from freezing. Due to heat storage operation freezing is not anticipated in this case.

The free space inside the RR140 pile is 120 mm and it is well enough for collector pipes. Typical size for borehole energy well is 115 mm in Finland. Hence, 40 mm polyethene double pipe (U-tube) is commonly used in boreholes as well as in piles.

In Toriparkki case RR140 piles were selected due to their load bearing capacity. Nevertheless, these types of micro piles can be used as energy collectors simultaneously when functioning as load bearing structures [23]. The main energy storage system quantities of Toriparkki energy system can be seen in Figure 5 and the construction site situation at June 2019 in Figure 6.

3.1 The solar thermal system built inside the market square

The annual heating energy demand of the project is after careful simulation calculated to 6.600 MWh. The solar thermal and waste heat energy system collects 11,2 GWh of heating energy annually. According to careful simulations of the heating energy flows, more than 42 % of the collected heating energy is annually lost by heat conduction to the surrounding clay. Also, the literature review on case studies of seasonal thermal energy storages in similar clay formations show that reaching a higher load/discharge-rate than 40 % is hardly possible.

The floor construction of the parking lot and surrounding shopping centre spaces consist of a concrete floor insulated from underneath by extruded polystyrene (XPS). Normally constructions like this would be insulated by the more cost-efficient expanded polystyrene (EPS). When building on top of a seasonal thermal energy storage the increase in water vapour pressure has to be blocked in the floor construction. Extruded polystyrene provides this water vapour block.

3.2 The seasonal thermal energy storage and peak energies optimization

The solar thermal system built inside the market square and the seasonal thermal energy storage is the result of a optimization of investment costs and life cycle costs performed by the NollaE-optimization software, which calculates energy losses according to the standards SFS-ISO 13370, SFS-EN 13790, SFS 5139, SFS-EN 308:1997, SFS-EN 13141-7, SFS-EN 12464-1, SFS-EN-ISO 13786, SFS-EN ISO 13790, SFS-EN 14511-2:2007, SFS-EN 16147 and SFS-EN 14511-3. The software also calculates peak heating demand, heat loads, construction costs and costs of using the building. In the process of optimization the software calculates a normal year of usage with altered construction-, HVAC-, architecture- and electrical solutions.

The optimization process was proceeded by a simulation of all the buildings attached. Every kWh of heating and cooling energy needed by these buildings were analysed and presented. The specific time of consumption and finally the size of the heating and cooling energy flows were charted. After a careful mapping of the energy flows, the NollaE-optimization software searched for all the 10.000 possible alternative solutions and combinations of solutions for providing heating and cooling energy with the smallest investment cost and smallest life cycle cost together with the greatest return on investment.

The software cuts the peak heating load for all the buildings with different constructional and HVAC-oriented combinations of measures. The peak heating load of the whole system was cut down from 10 MW to

http://doi.org/10.1051/e3sconf/202017216008

6,6 MW. The annual heating energy consumed in these buildings was cut down from 10.2 GWh to the current 6,6 GWh. This 6,6 GWh of annual heating energy was optimized to be produced by the most cost-efficient way possible, which in this project was utilizing the 23.500 m^2 market square as a solar collector and storing it to the 50 meters clay bed underneath the building. The result of the optimization is that the building owner saves annual 839.520 euros in heating and cooling costs.

Achieved thermal energy savings for predicted peak time amounted to 83,3 % for the space heating. Heat load for walking area surface heating decreased by 7,6 %. The whole heating system peak load decreased by 34 %. Annual energy savings for the whole heating system after optimization reached 35,3 %.

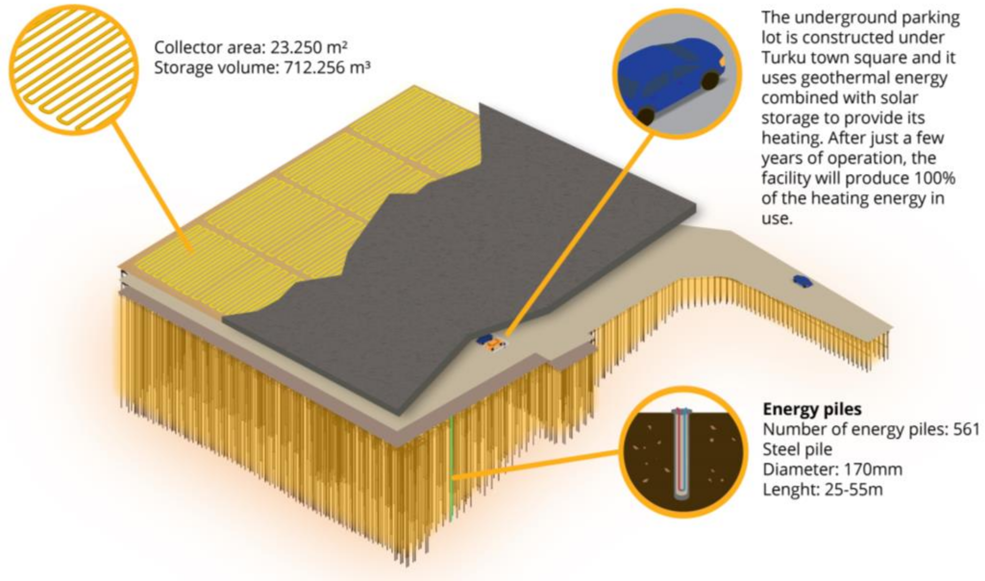

Fig. 5. Surface as a solar collector. Piles charging the clay storage in summer and discharging in winter.

Fig. 6. Toriparkki construction site at June 2019.

4 Conclusions

First, an overview of the urban underground spaces are presented in this study and following a case presentation of Turku underground parking lot/facility. This type of a building – underground parking lot – has been under construction in Turku since autumn 2018. This parking lot is first of its kind in many ways: 1) Never before underground parking lot has constructed into clay in Finland, 2) it is probably the first zero energy parking facility in Europe and 3) it has the biggest solar thermal energy storage in the world.

There are a growing number of facilities that use seasonal thermal energy storage (STES), enabling solar energy to be stored in summer for space heating use during winter. As the energy from the storage will be extracted and re-utilized months later, there is less need for producing energy. Thus re-utlization decreases total energy costs and emissions.

Thousands of BTES systems are built worldwide since 1970's. They are mainly utilizing industrial waste heat, and heat is distributed to customers via district heating net.

Turku market square underground parking lot (Turku Toriparkki) is introduced in this paper from the energy perspective. The parking facility has a seasonal thermal energy storage underneath. Thermal energy will be collected using market square stone pavement as a collector. In summer heat will be injected into the thick clay layer using the concrete piles that are supporting the building. In winter the heat is used to de-ice the pavement and to heat the parking facility.

After the literature review and general case presentation, the results of energy simulation and optimization of Toriparkki energy system are presented. The peak heating load of the whole system was cut down 34 % from 10 MW to 6,6 MW. The annual heating energy consumed in these buildings was cut down from 10.2 GWh to the current 6,6 GWh. The result of the optimization is that the building owner saves annual 839.520 euros in heating and cooling costs.

In a wider scope, this type of a Seasonal Thermal Energy Storages will have an important role in the future. As being part of the smart energy system, they can provide demand flexibility and synergies between consumers/prosumers and energy companies that are seeking common interfaces for new business opportunities. This is also the case in Turku Toriparkki. The planned system is a combination of solar energy, district heating, HVAC of the parking facility and energy storage. The energy system of the parking facility is interconnecting systems and a step towards sector coupling.

The case study locates in the heart of the city. This brings the project to follow for all of the citizens and raises common awareness of climate change actions. The whole construction project provided solution for many targets at the same time: More attractive and available city centre, more parking spaces, safer routes for bikers and confrontation of citizen, towards carbon neutral city and showing a smart way for utilizing solar energy otherwise to be wasted.

5 Progress tracking

The entire Toriparkki project is planned to be ended in 2021. Progress of this project could be tracked online using special webpage [46].

An English animation on Toriparkki energy system can be found from [47], where also Swedish and Finnish versions are available.

References

1. H. Rehman, J. Hirvonen, K. Sirén. Renew. Energy, Vol. **113** (2017)
2. A. Gabrielsson, M. Lehtmest, L. Moritz, U. Bergdahl. Heat storage in soft clay. Field tests with heating (70 °C) and freezing of the soil. Swedish Geotechnical Institute. Report 53 (1997)
3. M. Reuss, M. Beck, J.P. Muller. Solar Ener. Vol. **59**, Nos. 4-6, pp. 247 257 (1997)
4. https://www.turku.fi/en/new-turku-market-square/traffic/public-transport
5. Statistics Finland (Preliminary population structure by Month, Area, Sex and Information). http://pxnet2.stat.fi/PXWeb/pxweb/en/StatFin/StatFin__vrm__vamuu/statfin_vamuu_pxt_11lj.px/table/tableViewLayout1/
6. N. Bobylev. Land Use Pol., **26 (4)**, pp. 1128-1137 (2009)
7. Y. K. Qiao, F. L. Peng, S. Sabri, A. Rajabifard. Sust. Cities and Society, 101757 (2019)
8. X. Li, C. Li, A. Parriaux, W. Wu, H. Li, L. Sun, C. Liu. Tunnelling and Underground Space Tech., **55**, pp. 59-66 (2016)
9. H.Li, X.Li, C.K. Soh. Tunnelling and Underground Space Tech., **55**, pp. 67-82 (2016)
10. M.R. Doyle. Tunnelling and Underground Space Tech., **55**, pp. 83-95 (2016)
11. J.B.M. Admiraal. Tunnelling and Underground Space Technology. 21. 464-465. 10.1016/j.tust.2005.12.102. (2006)
12. K. Matsushita, S. Miura, T. Ojima. Tunnelling and Underground Space Tech., **8 (1)**, pp. 65-73 (1993)
13. H. Xue, J.C. Ho. Tunnelling and Underground Space Tech., **15 (1)**, pp. 101-115 (2000)
14. J.C. Ho, H. Xue, K.L. Tay. Building and Env., **39 (1)**, pp. 67-75 (2004)
15. P. J. Tulpule, V. Marano, S. Yurkovich, & G. Rizzoni. Applied Energy, **108**, pp. 323-332 (2013)
16. Energy efficient garage, https://patents.google.com/patent/US8650814B2/en
17. R. A. Kramer. Energy eng., **104 (6)**, pp. 23-38 (2007)
18. H. Brandl. Géotechnique, **56 (2)**, pp. 81-122 (2006)
19. Turku City Board desicion, 9th Feb 2015 https://www.turku.fi/en/housing-and-environment/environment/sustainable-development
20. D. Pahud, A. Fromentin, M. Hubbuch. Heat exchanger pile system of the dock Midfield at the Zürich airport. Detailed simulation and optimisation of the installation. Project report (1999)

21. Y. Hamada, H. Saitoh, M. Nakamura, H. Kubota, K. Ochifuji. Energy and Build., **39 (5)**, pp. 517-524 (2007)
22. T.D. Atmaja, R. Rahmayanti, V. Susanti, S. Utomo, D. Andriani, A.P. Wibawa, M. Mirdanies, H.M. Saputra, A. Santoso. Study on Energy Management System for Energy Saving on Semi Underground Rotary Parking Lot. International Conference on Sustainable Energy Engineering and Application 167-212 (2018)
23. R. Lautkankare, N. Salomaa, T. Arola, J. Lehtonen. Conference proceedings IFCEE: Recent Developments in Geotechnical Engineering Practice (2018)
24. D. Mangold, T. Schmidt, A. Dohna, D. Späh. Guideline for seasonal thermal Energy Storage systems to built environment, Solites, Steinbeis Research Institute for Solar and Sustainable Thermal Energy Systems, EU-FP7 project (2016)
25. B. Nordell. Large-scale thermal energy storages. Conference paper, Winter Cities 2000: Energy and Env. (2000)
26. https://www.businessfinland.fi/en/whats-new/news/2019/qheat-is-piloting-worlds-first-seasonal-geothermal-energy-storage/
27. T. Baser, J.S. McCartney. Renew. Energy, **147**, pp. 2582 -2598 (2020)
28. K. Kubiński, L. Szabłowski. Renew. Energy, Elsevier, **145 (C)**, pp. 2025-2033 (2020)
29. R. Lazzarin, M. Noro. Energy and Build., **174**, pp. 335-346, (2018)
30. M. Honkonen. Thermal energy storage concepts and their feasibility, Master thesis, Aalto University, Rock mechanics (2016)
31. I. Kukkonen, S. Peltoniemi. Physics and Chemistry of the Earth, **23, no. 3**, pp. 341-349 (1998)
32. GTK Geologian Tutkimuskeskus, Pohjaveden synty ja esiintyminen (In Finnish). Available: http://weppi.gtk.fi/aineistot/mp-opas/pohjav_esiintyminen.htm (2005)
33. T. Schmidt, D. Mangold, H. Müller-Steinhagen, Seasonal thermal energy storage in Germany, ISES Solar World Congress, (2003)
34. G. K. Pavlov, B. W. Olesen. Seasonal solar thermal energy storage through ground heat exchangers – Review of systems and applications, In Proceedings (2011)
35. S. Maanpää. Geological surveys, available in Finnish. Interview (2020)
36. R. Karhunen. Iniön ja Turun kartta-alueiden kallioperä. Suomen geologinen kartta 1:100000. Kallioperäkarttojen selitykset, lehdet 1041 ja 1043 [Pre-Quaternary rocks of the Iniö and Turku map-sheet areas. Explanation to the maps of Pre-Quaternary rocks, Sheets 1041 and 1043] (2004)
37. P. Lahermo, M. Ilmasti, R. Juntunen, M. Taka. The hydrogeochemical mapping of Finnish aquifers. Geochemical Atlas of Finland, part 1. (1990)
38. J.P. Lunkka, P. Johansson, M. Saarnisto, O. Sallasmaa. Quaternary glaciations – Extend and Chronology, Elsevier, **2 (1)**, pp. 93-100 (2004)
39. J. Niemelä, C-G. Sten, M. Taka, B. Winterhalter. Turun-Salon seudun maaperä. Suomen geologinen kartta 1:100 000. Maaperäkarttojen selitykset, lehdet 1043 ja 2021 [Quaternary deposits in the Turku-Salo map-sheet areas. Geological map of Finland 1:100 000. Explanation of the maps of Quaternary deposits, sheets 1043 and 2021] (1987)
40. J. Lehtonen. Underpinning project; owners´ views on technology, economy and project management, Doctoral dissertation, Aalto University (2011)
41. https://www.renor.fi/uutiset/2018/ainutlaatuinen-pohjavesihanke-askonalueella.html
42. J. M. Bloemendal. TU Delft. E-mail (2019)
43. S. Gehlin. The Swedish Geoenergy Center. E-mail (2019)
44. R. Lautkankare, J. Rantala, V. Sarola, H. Kanerva-Lehto. Hybrid energy micropiles in underpinning projects – combination of load bearing structures and geothermal energy field. ISM 2014, Poland (2014)
45. Ministry of economic affairs and employment of Finland. https://tem.fi/artikkeli/-/asset_publisher/kolmelle-uusiutuvan-energian-suurelle-demolaitoshankkeelle-yhteensa-13-4-miljoonaa-euroa-investointitukea
46. https://torilive.fi/
47. https://www.youtube.com/watch?v=EtJ9sFUG1kg