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Heat recovery from exhaust air as a thermal storage energy source for geothermal energy piles

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Abstract

In pursuit of EU directive 2010/31/EU energy performance targets towards design of nearly zero-energy buildings consideration of renewable energy sources in the design is expected. Application of ground-source heat pump (GSHP) and energy piles in cold climate conditions for utilization of renewable geothermal energy may results in GSHP plant high seasonal coefficient of performance (SCOP) as long as source of thermal storage is considered in plant design. This numerical study investigates exhaust air of air handling unit (AHU) as a source of thermal storage for geothermal plant with energy piles, that can be utilized via air-to-liquid heat exchanger installed at the exhaust side of AHU after the rotor heat exchanger and exhaust fan. Modelling is performed in dynamic whole year simulation environment Equa IDA-ICE, where reference commercial hall-type building model is coupled with detailed custom heat pump plant. Exhaust air thermal storage capacity in multiple energy piles field configurations with varying soil conditions, distance between piles and pile lengths is analyzed. Results revealed that exhaust air thermal storage appears to be highly cost effective solution. Graphical figures presented in this paper can be further applied for preliminary exhaust air thermal storage capacity assessment in buildings with energy piles.

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Keywords: heat pump plant; energy piles; nZEB; thermal storage; IDA-ICE; whole building simulation

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1. Introduction

Achievement of the EU directive 2010/31/EU [1] energy performance targets by the end of 2020 considers application of renewable energy sources in the design of nearly zero-energy buildings (nZEB), that are required to be built since abovementioned date. Geothermal energy, as a renewable energy source, has proven itself in measurements [2-3] to be efficiently utilized by a ground-source heat pump (GSHP) yielding high GSHP seasonal coefficient of performance (SCOP) of up to 4.5 and overall geothermal plant SCOP (with control and distribution losses) up to 3.9. According to a review on worldwide application of geothermal energy [4] total installed worldwide GSHPs capacity has grown 2.15 times in the period of 2005 to 2010 and application of GSHP is registered in 78 countries around the globe.

Geothermal plant consists of a GSHP and ground heat exchanger (GHE). Buildings with pile foundation are attractive for installation of heat exchange pipe loop into individual piles making piles act not only as building bearing component, but also as ground heat exchanger known as energy pile foundation [5]. As the installation of heat exchange piping into foundation pile compared to the drilling of a new borehole is much cheaper, energy piles tend to be a very cost effective GHE solution. Because the layout of energy piles is in most cases defined by the foundation plan, thermal interferences between closely located adjacent piles appear. To account for prior mentioned thermal interactions, sizing and assessment of energy piles performance is generally carried out with help of numerical modelling. Detailed aspects and consideration that should be accounted in the design of energy piles GHE are described in detail in study conducted by Fadejev and Kurnitski [6]. In cold climate regions, building annual heat balance is generally heating dominated. Therefore, energy piles unbalanced heat extraction/rejection of ground heat produces decrease in heat pump plant yields [7] over the years of operation resulting in higher building operational cost. To stabilize geothermal plant heat production, thermal storage is generally applied [8]. There are numerous options of thermal storage sources suitable for the application in GSHP plant - some of most common are solar thermal storage and cooling tower i.e. dry cooler thermal storage. Reda [9] conducted a numerical study presenting the benefits of solar thermal storage in a GSHP plant with a borehole field type ground heat exchanger (GHE), where application of solar thermal storage helped to improve GSHP plant SCOP from 1.6 to 3.0. Allaerts et al. [10] modelled the performance of a GSHP plant with dual borehole field and active air source storage in TRNSYS, where cooling tower i.e. dry cooler was applied as a thermal storage source. As a results of thermal storage application, overall size of borehole field was reduced by 47% compared to the same capacity single borehole field plant without thermal storage.

Additional possible source of thermal storage is exhaust ventilation air of air handling unit (AHU) that can be utilized via air-to-liquid heat exchanger installed at the exhaust side of AHU after the rotor heat exchanger and exhaust fan. Despite the low temperature of exhaust air after the rotary heat exchanger during the heating season, it is still most of the time higher than the temperature in GHE loop of operating heat pump. Therefore, prior mentioned thermal storage solution may become very cost effective.

This study focuses on potential investigation of exhaust air heat exchanger coupled with air handling unit as a thermal storage energy source for geothermal plant with energy piles. A small scale parametric study is conducted with key parameters – specific exhaust air flow rate, soil properties, step between energy piles, their length and size of energy piles field. Modelling is performed in dynamic whole year simulation environment Equa IDA-ICE, where reference model of commercial hall-type building is coupled with transient heating/cooling geothermal plant with energy piles and exhaust air thermal storage. Energy piles are modelled with three-dimensional finite difference IDA-ICE borehole model extension, where detailed geometry of pile inner components and location of piles according to foundation plan are defined. Thermal interactions between soil, energy piles, pipe legs and upward/downward flowing fluid are modelled with accountancy for thermal capacitances of each component material properties. Heat pump, air handling unit and exhaust air heat exchanger with conveyance and control are modelled with standard IDA-ICE library components.

Results of numerical study are presented in graphical form suitable for assessment of exhaust air thermal storage potential based on the energy piles configuration, soil properties and amount of exhaust air flow passing through air-to-liquid heat exchanger. A case without thermal storage is contrasted against case with exhaust air thermal storage to assess possible reduction of energy piles field length. Additionally, exhaust air thermal storage yield is compared to solar thermal storage via calculation of solar collector effective area with equivalent yield.

2. Methods

The modelling in IDA ICE was performed in advanced level interface, where user can manually edit connections between model components, edit and log model specific parameters, observe models code. An early stage building optimization (ESBO) plant, which is a part of a standard IDA model library, was utilized to generate the plant model. Abovementioned plant and model of standard air handling unit was modified to meet the design intent geothermal plant with exhaust air thermal storage. A more detailed insight on geothermal plant modelling in IDA-ICE is presented in [6].

2.1. Building model data

Modelled geothermal plant with energy piles and exhaust air thermal storage was coupled with a reference commercial hall-type building model presented on Fig. 1, which geographical location is Hämeenlinna, Finland. Ambient boundary conditions, regarding local weather data were described in Helsinki test reference year climate file [11] and applied in the simulation.

In cold climate conditions of Finland, buildings indoor climate requirements are generally ensured with heating. Building's heating and cooling demand is met with radiant heating/cooling panels, which efficiency is fixed to 0.9. Table 1 presents a detailed overview of general parameters describing the building model.

Descriptive parameter	Value				
Location	Finland				
Net floor area, m ²	1496.5				
External walls area, $U = 0.17 \text{ W}/(\text{m}^2 \text{ K}), \text{ m}^2$	1199				
Roof area, $U = 0.09 \text{ W}/(\text{m2 K}), \text{ m}^2$	1475				
External floor area, $U = 0.24$ W/(m2 K), m2	1496.5				
Windows area, SHGC = 0.55, U = 1.0 W/(m ² K), m ²	158				
External doors, $U = 1.0 \text{ W}/(\text{m}^2 \text{ K}), \text{m}^2$	67				
Heating set point, °C	18				
Cooling set point, °C	25				
Occupancy/lighting schedule	8:00-17:00(6d)				
AHU operation schedule	7:00-18:00(6d)				
Occupants, 1.2 met, 0.8 clo, no./m ² ,(W/m ²)	0.0235,(2)				
Lights load, W/m ²	19				
Equipment load, W/m ²	1				
AHU air flow, l/sm ²	0.1 - 2.0				
AHU heat recovery, %	80				
Air tightness, m ³ /m ² h	4 @50 Pa				
Supply air temperature, °C	18				
Heating/cooling room units	radiant panels				

Table 1. Building model parameters.

Reference building model internal gains, occupancy/equipment/lighting schedules, air handling unit operation schedule, heating/cooling set points were setup according to National Building Code of Finland 2012 – Section D3 on Energy Management in Buildings [12].



Fig. 1. Model of commercial hall-type reference building in IDA-ICE.

2.2. Numerical study plan

Compiled numerical study plan consists of 120 studied cases, where varying case parameters and their values are presented with detailed description in Table 2.

Number of studied cases	120
Specific exhaust air flow, $l/(s m^2)$	0.1, 0.25, 0.5, 1.0, 2.0
Soil heat conductivity, W/(m K)	1, 3
Distance between piles, m	3, 6
Fields for 40 meter deep piles	2x2, 3x3, 4x4
Fields for 10 meter deep piles	4x4, 6x6, 8x8
Depth of piles, m	10, 40
Case parameter	Values

Fields of energy piles coupled with the reference building model for assessment of exhaust air thermal storage capacity for 10 meters deep energy piles are presented on Fig. 2.

													57	58	59	60	61	62	63	64
													49	50	51	52	53	54	55	56
						31	32	33	34	35	36		41	42	43	44	45	46	47	48
						25	26	27	28	29	30		33	34	35	36	37	38	39	40
	13	14	15	16		19	20	21	22	23	24		25	26	27	28	29	30	31	32
	9	10	11	12		13	14	15	16	17	18		17	18	19	20	21	22	23	24
	5	6	7	8		7	8	9	10	11	12		9	10	11	12	13	14	15	16
(A)	1	2	3	4	(B)	1	2	3	4	5	6	(C)	1	2	3	4	5	6	7	8

Fig. 2. (a) Energy piles field nr 1, length 10 meters. (b) Energy piles field nr 3, length 10 meters. (c) Energy piles field nr 5, length 10 meters.

Fields of energy piles coupled with the reference building model for assessment of exhaust air thermal storage capacity for 40 meters deep energy piles are presented on Fig. 3.

					13	14	15	16
	7	8	9		9	10	11	12
3 4	4	5	6		5	6	7	8
(A) 1 2	(B) 1	2	3	(C)	1	2	3	4

Fig. 3. (a) Energy piles field nr 2, length 40 meters. (b) Energy piles field nr 4, length 40 meters. (c) Energy piles field nr 6, length 40 meters.

It is worth to note, that energy piles fields overall length of smaller (10 m) and longer (40 m) piles are equivalent for more precise comparison reasons.

2.3. Exhaust ventilation air thermal storage modelling

Fundamental scheme presented on Fig. 4 describes the connections of each individual components of geothermal heat pump plant with energy piles and exhaust air thermal storage.



Fig. 4. Fundamental scheme of geothermal plant with exhaust ventilation air thermal storage.

In order to prevent the formation of the ice in the ground and possible frost heave, geothermal loops brine outlet temperature should not drop below 0...-1 °C. Therefore, circulation pump (P-2) will stop when measured (T2) brine outlet temperature drops below the set point of 0 °C. Condenser side of the heat pump is connected to a hot buffer

tank, in which heat carrier temperature is maintained according to a supply schedule temperature that is dependent on outdoor air temperature value with its maximal value of supply side +50 °C at design outdoor air temperature conditions of -26 °C.

Exhaust air heat exchanger is applied as a thermal storage source in energy piles loop. Exhaust air thermal storage is controlled according to a temperature difference (ΔT) set point logics, where two temperatures are measured and desired value of ΔT is maintained. In exhaust thermal storage loop $\Delta T = 4K$. Measured temperatures in thermal storage loop on Fig. 4 are T3A and T3B. Whenever T3A temperature value is higher than 4K of T3B temperature value, pump P-3 starts it operation until the temperature of T3A reaches the desired $\Delta T = 4K$.

A model of custom made air handling unit with exhaust air thermal storage and connection to geothermal plant with energy piles in IDA-ICE is presented on Fig. 5 (b) and compared to a standard air handling unit depicted on Fig. 5 (a) available in IDA-ICE as a standard library component.



Fig. 5. (a) Standard air handling unit in IDA-ICE. (b) Air handling unit with exhaust air thermal storage in IDA-ICE.

As it can be observed on Fig. 5 (b), exhaust air thermal storage AHU model consists of 8 additional models connected to the standard air handling unit. These models are – air-to-liquid heat exchanger, expansion vessel, borehole model (where energy piles fields are described), standard library heat exchanger model, circulation pumps, temperature sensor reporting the floor slab temperature to the borehole model for it to perform as energy piles and dT control macro. More detailed description of custom plant modelling in IDA-ICE is presented in [6].

2.3.1. Energy piles

Energy piles field in GSHP plant was modelled with IDA-ICE borehole model extension. Borehole model applies finite difference to calculate a number of temperature fields that combined by superposition generate the threedimensional field. Model accounts for heat transfer between U-pipe, upward and downward flowing liquid, grout, ground, ground surface and ambient air. The length of each pile is assumed to be equal and ground homogeneous. Model considers the input of parameters (Table 3), which describe thermal and physical properties of ground, pipe, grout and brine. More detailed description of IDA-ICE mathematical model and its parameters is presented in [6].

Descriptive parameter	Value
Energy piles amount, pcs	4 - 64
Energy piles depth, m	10 or 40
Energy pile diameter, mm	115
Distance between energy piles, m	3 or 6
Pipes outside walls distance, mm	52.4
U-pipe outer diameter, mm	25
U-pipe inner diameter, mm	20.4
Ground heat conductivity, W/(m K)	1 or 3
Ground volumetric heat capacity, kJ/(m3 K)	2019
Ground average annual temperature, °C	5.62
Energy pile grouting heat conductivity, W/(m K)	1.8
Grout volumetric heat capacity, kJ/(m3 K)	2160
Pipe material heat conductivity, W/(m K)	0.3895
Pipe volumetric heat capacity, kJ/(m3 K)	1542
Brine ethanol concentration, %	25
Brine freezing temperature, °C	-15
Brine heat conductivity, W/(m K)	0.43
Brine volumetric heat capacity, kJ/(m3 K)	4023
Brine density, kg/m3	969
Brine viscosity, Pa s	0.006
Borehole thermal resistance, (m K)/W	0.11
Prandtl number	57

Table 3. Energy piles field modelling parameters.

3. Results

Results of two cases with and without exhaust thermal storage in simulation with duration period of 20 years are depicted on Fig. 6 to briefly present the long-term potential of exhaust air thermal storage. In case with exhaust air thermal storage, energy piles field of Fig. 3 (a) managed to extract ca 25% more heat compared to similar field of energy piles without thermal storage.



Fig. 6. Exhaust ventilation air thermal storage application performance.

Therefore, a significant 25% reduction of a pile field length due to application of exhaust air thermal storage to maintain equivalent yield compared to a non-storage case is expected.

Trend of increasing yield over the years of operation in case without thermal storage on Fig. 6 can be explained by the floor slab heat loss, which acts as a natural source of thermal storage for energy piles, which modelling and limitations in IDA-ICE is discussed in [6]. Inlet temperatures of GSHP evaporator corresponding to previous two cases are described on Fig. 7. It can be observed on Fig. 7 (a), that in case without thermal storage maximal temperature of ca 10 °C is reached in summer of 20th year, while with exhaust air thermal storage on Fig. 7 (b) evaporator inlet temperature peaked during the summer at ca 23 °C every single year. It should be noted, that in case with thermal storage presented on Fig. 7 (b) more like extreme scenario is presented, as the overall length of pile field (160 m) is comparatively small to what would be considered in real scenario, when pile field is sized based on the its possible geothermal yield and reasonable heat pump power. Therefore, temperature levels with exhaust air storage would be in most cases lower in summer, than presented on Fig. 7 (b). Temperature levels presented on Fig. 7 are good indication of possibility to utilize geothermal loop as a source of direct "free cooling" to meat partially buildings cooling demand even along with exhaust air thermal storage application.



Fig. 7. (a) Energy piles field nr 1 without thermal storage (b) Energy piles field nr 1 with exhaust air thermal storage (2.0 l/s m²).

Results of 120 simulated cases were applied in preparation of exhaust air thermal storage potential assessment figures (Fig. 8 - 10), that are suitable for preliminary evaluation of exhaust air thermal storage potential in specific energy piles field based on the distance (step) between energy piles, their length, soil thermal conductivity and available exhaust air amount. Figures legend first numbers e.g. 2x2 correspond to the applied field, code L40 corresponds to length of piles 40 meters and code S3 corresponds to distance (step) between piles of 3 meters.



Fig. 8. (a) Thermal storage in pile fields nr 1 and 2, soil $\lambda=1$ W/(mK). (b) Thermal storage in pile fields nr 1 and 2, soil $\lambda=3$ W/(mK).

Numerical study results for energy piles field nr 1 on Fig. 2 (a) and nr 2 on Fig. 3 (a) are presented on Fig. 8, where evaporator sizing power per meter of pile of a heat pump covering 98% of the reference building heat demand at specific air flow 0.1 $l/(s m^2)$ corresponds to 65 W/m and at specific air flow 2.0 $l/(s m^2)$ corresponds to 243 W/m.

It can be observed, that higher amount of heat can be stored in soil $\lambda=3$ W/(mK) on Fig. 8 (b) compared to soil $\lambda=1$ W/(mK) on Fig. 8 (a), with maximal difference of up to ca 1.4 times obtained at specific air flow rate of 2.0 l/(s m²). Distance between piles of 3 meters in case 2x2/L40/S3 slightly impacts the storage capacity being ca 9% smaller compared to the same field with distance of 6 meters (case 2x2/L40/S6). Overall length of energy piles in pile field nr 1 and nr 2, which results are presented on Fig. 8 are equal to both 160 meters. Therefore, impact of energy pile length on thermal storage capacity of a field can be also assessed. According to Fig. 8 pile field consisting of four 40 meter piles was ca 1.3 times more efficient at storing exhaust air heat than pile field consisting of 16 piles of 10 meter length each.



Fig. 9. (a) Thermal storage in pile fields nr 3 and 4, soil $\lambda=1$ W/(mK). (b) Thermal storage in pile fields nr 3 and 4, soil $\lambda=3$ W/(mK).

Numerical study results for energy piles field nr 3 on Fig. 2 (b) and nr 4 on Fig. 3 (b) are presented on Fig. 9, where evaporator sizing power per meter of pile of a heat pump covering 98% of the reference building heat demand at specific air flow 0.1 $l/(s m^2)$ corresponds to 29 W/m and at specific air flow 2.0 $l/(s m^2)$ corresponds to 108 W/m.

Overall length of piles for pile fields nr 3 and 4 on Fig. 9 is 320 meters i.e. double of previously discussed. Compared to pile fields with total piles length of 160 meters, storage capacity due to doubling the field sizing decreased in soil $\lambda=1$ W/(mK) by ca up to 1.3 times and in soil $\lambda=3$ W/(mK) by ca up to 1.4 times.



Fig. 10. (a) Thermal storage in pile fields nr 5 and 6, soil $\lambda=1$ W/(mK). (b) Thermal storage in pile fields nr 5 and 6, soil $\lambda=3$ W/(mK).

Numerical study results for energy piles field nr 5 on Fig. 2 (c) and nr 6 on Fig. 3 (c) are presented on Fig. 10, where evaporator sizing power per meter of pile of a heat pump covering 98% of the reference building heat demand at specific air flow $0.1 \text{ l/(s m}^2)$ corresponds to 16 W/m and at specific air flow $2.0 \text{ l/(s m}^2)$ corresponds to 61 W/m.

Overall length of piles for pile fields nr 5 and 6 on Fig. 10 is 640 meters i.e. double of previously discussed. Compared to pile fields with total piles length of 320 meters, storage capacity due to doubling the field sizing decreased in soil $\lambda=1$ W/(mK) by ca up to 1.25 times and in soil $\lambda=3$ W/(mK) by ca up to 1.3 times.

To compare exhaust air thermal storage potential against solar thermal storage, a case with flat plate solar collectors was simulated, where obtained solar storage capacity per square meter of solar collector was ca 750 kWh/(m² a). Therefore, application of exhaust air thermal storage in case 2x2/L40/S6 of energy piles field nr 2 on Fig. 3 (b) in soil λ =1 W/(mK) at specific air flow rate of 1.0 l/(s m²) would store ca 10.4 MWh of heat, which corresponds to ca 14 m² of solar collector area.

4. Conclusion

Numerical study revealed that application of exhaust air heat exchanger coupled with air handling unit as a thermal storage source for geothermal heat pump coupled with energy piles may become economically very attractive due to relatively low investment cost and potentially high thermal storage energy yield resulting in short payback period. According to simulations with duration period of 20 years, application of exhaust air thermal storage produced geothermal energy yields of ca 25% higher compared to case without thermal storage. Limits of exhaust air thermal storage potential are defined by the temperature of exhaust air, which in theory is the limit of possible temperature that soil can be heated up to. Therefore, in buildings with additional thermal storage need solar storage is the additional solution to be applied.

Graphs obtained and presented as a result of numerical study can be further applied in preliminary assessment of exhaust air thermal storage potential for different pile field configurations, in different soil conditions based on the exact exhaust air amount. Presented model of GSHP plant with exhaust air thermal storage in IDA-ICE can also be utilized for more expanded study. Energy piles length of simulated cases is equivalent to the evaporator sizing power range of 16 W/m to 243 W/m for conditions, when heat pump condenser power is sized to meets 98% of the building heat demand. From the perspective of exhaust thermal storage capacity, more favorable conditions with increased amount of stored heat were with longer piles, wider distance between piles and higher soil heat conductivity.

When exhaust air thermal storage was compared against solar storage, similar amount of stored heat obtained with exhaust air thermal storage system was equivalent to a system of 14 m² flat plate solar collector.

Research in this field will be continued in form of energy piles parametric study, which is required to assess the performance of different field configurations and help in preparation of design guidelines for buildings with geothermal energy piles.

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