13th IEA Heat Pump Conference 2020

13th IEA Heat Pump Conference
April 26-29, 2021 Jeju, Korea

Design of a gas-driven hybrid adsorption heat pump coupled to geothermal heat exchangers for retrofitting applications

Valeria Palomba[a*], Antonino Bonanno[a], Davide La Rosa[a], Stefan Löwe[b], Ralph Herrmann[b], Andrea Frazzica[a]

[a]Istituto di Tecnologie Avanzate per l'Energia CNR-ITAE, Messina (Italy)
[b]Fahrenheit GmbH, Halle (Germany)

Abstract

The need for retrofitting of residential buildings with energy efficient solutions requires for the development of a wide range of solutions, suitable for different climates and buildings. In the present paper, a concept based on a gas-driven sorption heat pump using geothermal source for evaporation is presented. A dynamic luped-parameter model was implemented in Dymola and used to verify the flexibility of the system in terms of response to variable load and comfort conditions. The outcomes of the activity will be used to propose an improved design of the system.

Keywords: sorpion; geothermal; residential.

1. Introduction

The building heating and cooling sector is accounting for a relevant amount of primary energy consumption in Europe. So far, according to EU, less than 20% of heating and cooling is provided by renewable sources. Heat pumps represent an innovative solution to increase the share of renewables at the building scale, thus participating to the decarbonisation of the heating and cooling sector [1]. In order to make them suitable for different climates, keeping high performance in terms of COP/EER also in severe conditions, the exploitation of geothermal energy as ambient heat source/sink is considered of great interest [2]. In particular, advantages of geothermal heat pumps include high efficiencies (COPs of ground source heat pumps are in the range 3–5 while COPs of air source heat pumps are in the range 2.3–3.5) and low operating costs [2]. The application of ground-source heat pumps was investigated and proven in a wide variety of climates, including European Mediterranean and Continental [3,4], Turkey [5], Iran [6] and China [7], as well as in different building typologies, i.e. residential and commercial [4,8]. However, the exploitability of this resource in the built environment, for retrofitting applications, becomes quite challenging due to both, technical and regulatory constraints that limit the drilling procedures for the ground source heat exchangers (GSHEX) installation.

With this mind, the EU funded GEOFIT [9] project aims at the deployment of innovative geothermal heat pump solutions for retrofitting applications. Particularly, an innovative hybrid geothermal heat pump will be developed, tested and installed in two demo sites. Different hybrid geothermal heat pumps have been proposed, such as a solar-geothermal heat pump able to exploit alternatively the heat from vacuum collectors or the ground [10] or a hybrid configuration with the cooling tower and the ground loops connected together [11,12].

Instead, in the present work, the hybrid solution proposed consists of a hybrid gas-driven hybrid adsorption/electric heat pump Indeed, this combination of thermally and electrically driven HP, despite the lower thermal COP compared to an electrical vapour compression chiller, can be efficiently operated with a smaller size GSHEX. This will make the heat pump more suitable for applications with reduced space availability.

In order to assess the feasibility of such a hybrid solution, a detailed dynamic model was developed in Dymola environment. Adsorption heat pump and gas boiler were modelled by means of TIL Media Library, TIL Suite and self-developed components to match the specific characteristics of the hybrid unit developed. Particular focus was put on the control strategy for enhancing the comfort level achievable by the retrofit of existing systems with the hybrid solution proposed. A first prototype will be developed by Fahrenheit GmbH which will be tested at the CNR ITAE lab subsequently.

2. The GEOFIT sorption solution

The core of the hybrid sorption heat pump developed within GEOFIT is a gas-driven sorption heat pump, whose main components are shown in Figure 1. It is based on the two-modules layout from Fahrenheit GmbH commercial system. Each module consists of an adsorber/desorber and an evaporator/condenser. The desorber is connected through the HTF circuit to the gas boiler that allows the regeneration of the sorption material. At the same time, through the vacuum circuit, the refrigerant flows from the desorber to the condenser, that supplies heat at the temperature level requested for space heating. The adsorber is connected in parallel to the condenser through the HTF circuit. The vacuum circuit allows the flow of the refrigerant from the evaporator to the adsorber. The ground heat exchanger allows the use of the soil as heat source for evaporation. The useful effect delivered to the user is represented by the adsorption heat and condensation heat.

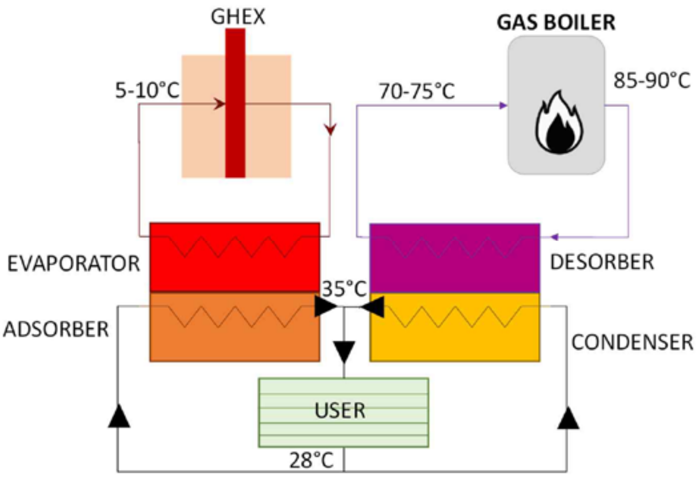

Figure 1: Main layout and thermal levels for GEOFIT hybrid gas-driven heat pump.

The main advantages in the utilization of such thermally-driven heat pumps as retrofitting solutions lies in the possibility of using shallow GSHEXs with a superficial area significantly lower than that needed when the heating system is represented by a vapour compression electrically-driven heat pump.

A schematic of a possible integration of the proposed gas-driven hybrid heat pump is depicted in Figure 2. It is clear that the gas boiler is exploited both to drive the desorption process and to provide domestic hot water (DHW) to the user. The typical distribution system used to increase the heat pump efficiency is a floor heating system, while GHEX is used to provide heat of evaporation in winter and to dump heat of condensation in summer.

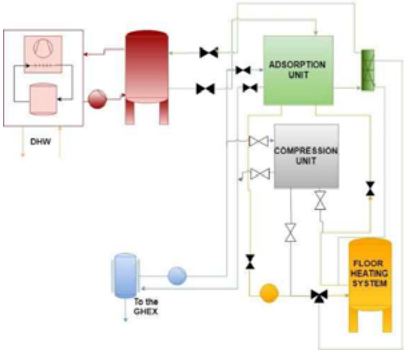

Figure 2: Schematic of the integration of the hybrid heat pump coupled to a gas boiler and the space heating system.

3. The modelling approach

The modelling approach used is schematically shown in Figure 3: Modelica language and Dymola commercial software were chosen as simulation environment. The main reasons for such a choice are the possibility of creating acausal and easily reusable models that, thanks to the FMU functionality of Dymola, can be easily exchanged and integrated in other simulation environments[13,14]. In order to model the refrigerant, the Heat Transfer Fluid (HTF) and the main components of the system, the commercial libraries included in TIL Suite were employed. Correspondently, the same structure as for components already included in the libraries, based on a cell level and a component level was employed also for the self-developed models. In particular, standard models based on liquid cells were employed to model the heat exchanger and heat transfer correlations, whereas self-developed model were used for the sorption equilibrium and the vapour/liquid control volume of the evaporator/condenser. The gas boiler was modelled considering a constant thermal power and an efficiency variable with part load and return temperature. All the components are properly managed thanks to specifically developed controls. The main equations of the model are presented in Table 1, while for a more detailed description of the Dymola model for the sorption unit, the reader is referred to [15].

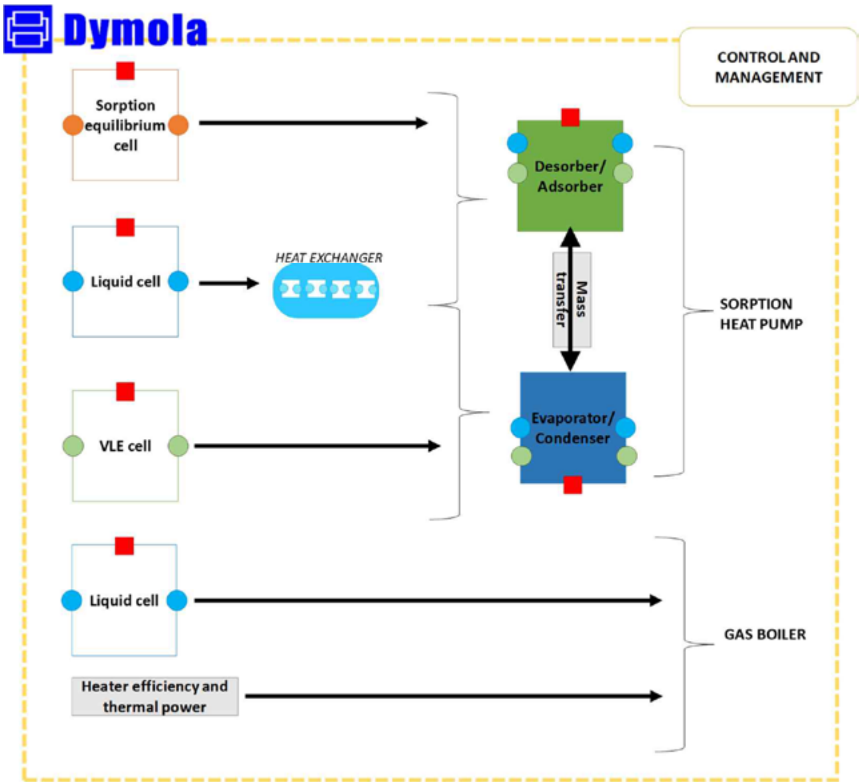

Figure 3: Modelling approach.

4. System control and management

In order to give indications on the best management strategy for the hybrid heat pumps and its integration in retrofitted systems, different controls were implemented and evaluated. In particular, three possible options for controlling the system were considered:

a. Variable flow rate of the pumps according to part load;
b. Step variation of the cycle time of the adsorption unit using the load requested by the user as target variable;
c. Step variation of the cycle time of the adsorption unit using the temperature in the user circuit as target variable.

The models for such components were developed in Dymola using existing components from Modelica Standard Library.
Since the main goal for the system under the GEOFIT activity here presented is the retrofitting of existing heating systems in different climates, two key elements play a particularly significant role:

1. the design of components, that must be as compact as possible;
2. the possibility of ensuring the same level of comfort and a flexible operation, in terms of adaptivity to the load of the building.

The first goal can be achieved thanks to the use of zeolite/water working pair, applying the patented crystallization technique developed by Fahrenheit [16], that has a significant higher power density when compared to standard silica gel/water systems on the market [17].

Instead, the second goal was the focus of the numerical activity here presented. Two key aspects were evaluated: the possibility of delivering a constant temperature to the user under different climatic conditions and the proper management of the sorption unit to be adaptable to user load.

Table 1: List of main equations used for the model implementation.

Component		**Equation**	
Adsorber	Mass balance sorbent cell	$\dot{m}_{ref} = \dot{m}_{evap} + \dot{m}_{cond}$	(1)
	Energy balance sorbent cell	$\left(m_{sorb}\, c_{p_{sorb}} + w \cdot m_{sorb}\, c_{p_{ref}}\right)\frac{dT_{sorb}}{dt} = \dot{Q}_{fbw} + \dot{m}_{ref}\, h_{ads} - m_{sorb}\, c_{p_{sorb}}\, T_{sorb}\, \frac{dw}{dt}$	(2)
	Mass balance adsorber HEX	$0 = \dot{m}_{in} + \dot{m}_{out}$	(3)
	Energy balance adsorber HEX	$m_{fluid}\, c_{p_{fluid}} \frac{dT_{fluid}}{dt} = \dot{m}_{fluid}\, c_{p_{fluid}} \left(T_{fluid_{in}} - T_{fluid_{out}}\right) + \dot{Q}_{fbw}$	(4)
	Heat transfer sorbent/HEX	$\dot{Q}_{fbw} = (\alpha S)_{ads} (T_{sorb} - T_{fluid})$	(5)
	Sorption equilibrium	$w = w_0 \exp(-bA)$	(6)
		$A = -RT_{sorb} \log \frac{p_{ads}}{p_{sat}}$	(7)
Vapor Liquid Equilibrium (VLE) volume evaporator/ condenser	Mass balance	$\frac{dm}{dt} = \dot{m}_v + \dot{m}_l$	(8)
	Energy balance	$\frac{dU}{dt} = \dot{H}_v + \dot{H}_l + Q_{fbw}$	(9)
	Mass balance HEX	$0 = \dot{m}_{in} + \dot{m}_{out}$	(10)
	Energy balance HEX	$m_{fluid}\, c_{p_{fluid}} \frac{dT_{fluid}}{dt} = \dot{m}_{fluid}\, c_{p_{fluid}} \left(T_{fluid_{in}} - T_{fluid_{out}}\right) + \dot{Q}_{fbw}$	(11)
	Heat transfer refrigerant/HEX	$\dot{Q}_{fbw} = (\alpha S)_{evap/cond} (T_{VLE} - T_{HEX})$	(12)
	Additional equations	$p_{VLE} = p_{sat}(T_{VLE})$	(13)
Mass transfer	Mass balance	$\dot{m}_{ref} = \dot{m}_{in} + \dot{m}_{out}$	(14)
	Linear Driving Force	$\dot{m}_{ref} = m_{sorb} \frac{dw}{dt} = m_{sorb}\, \beta(w_{eq} - w)$	(15)
	Mass transfer coefficient	$\beta = \frac{15D}{r_{sorb}^2}$	(16)
Gas boiler	Thermal power output	$\dot{Q}_{fbw} = \dot{Q}_{nominal}\, \eta$	(17)
	Efficiency	$\eta = a * T_{w_{in}} + b * T_{w_{in}}{}^2 + c * T_{w_{in}}{}^3 + d * T_{w_{in}}{}^4 - e * PL + f * \left(T_{w_{in}} * PL\right) - g * \left(T_{w_{in}}{}^2 * PL\right) + h$	(18)

5. Results

To evaluate the adaptability of the heat pump to a variable user load, a signal with changing load (between 4 kW and 8 kW) was used, aiming at simulating a variable user demand. The first approach, based on varying the heat transfer fluid flow rate, resulted not robust enough to let the adsorption machine being properly operated. Accordingly, the control strategy based on the variation of adsorption cycle time as a function of user load was implemented. To this aim, a multi-switch control was used, able to switch between different cycle periods as a function of the expected requested power. Clearly, the higher is the power demand the lower is the cycle time, in order to enhance the average heating capacity provided by the adsorption module, whose behaviour is intrinsically discontinuous due to the physics of the adsorption process[18]. This control is not based on a linear variation of the cycle time, but rather a step variation is investigated. To demonstrate the effect of the variable cycle time on the average power, in Figure 4 the output power provided by the adsorption heat pump is showed. The adsorption/desorption cycle time variation is clearly visible. The average heating power provided increases from about 3 kW at 800 s cycle time up to 5 kW for 200 s cycle time.

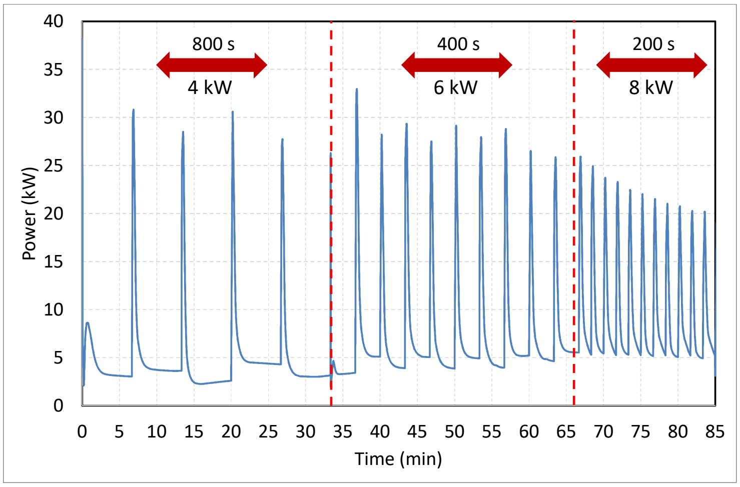

Figure 4: Adsorption machine output power (adsorption/desorption cycle control as a function of the load)

Analysing the temperature of water provided to the user Figure 5) it could be noted that the control works properly when the load is 3 kW and the cycle time is 800 s. Differently, it tends to deviate from the target when the power increases, most probably because the cycle time is reduced too much. This means that, to achieve a proper management, a continuous variation of cycle time according to the measured values of the temperature at each sampling time is needed.

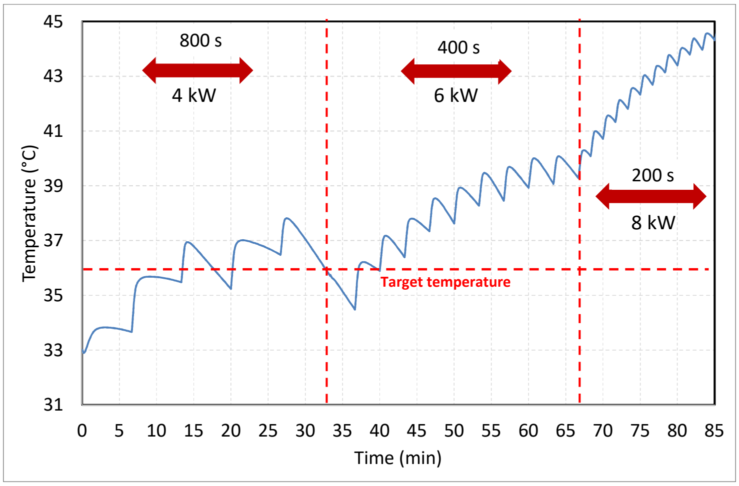

Figure 5: Temperature delivered to the user (adsorption/desorption cycle control as a function of the load)

From such results, it is clear that, to get comfort conditions, it is necessary to use a control that allows a finer tuning in terms of temperatures delivered to the user. Therefore, a second control was developed, that manages in real time the adsorption/desorption cycle time as a function of the temperature delivered to the user. The control compares the signal coming from the T_{user} sensor with the set point (e.g. 35°C); if the measured temperature is lower than the set point, this means that the heating load is higher than the one produced by the adsorption machine, therefore the adsorption/desorption cycle time is reduced. If the measured temperature is higher, than the cycle time is increased, because the requested heating power is decreasing. Compared to the previous case, the cycle time is not imposed a priori, i.e. there is not a predetermined cycle time as a function of the temperature, but rather a user-defined Δt is used for following the user heating demand:

- When the feedback signal $T_{user,measured}$-$T_{user,set}$ is <0, the cycle time is reduced of an amount Δt;

- When the feedback signal $T_{user,measured}$-$T_{user,set}$ is >0, the cycle time is increased of an amount Δt;

Threshold values for minimum and maximum cycle time are imposed as well, to avoid inefficient operation of the unit. Figure 6 reports the power delivered by the adsorption machine for a 30 min operation at variable load with the implemented control. The feedback loop operates changing the cycle time with a Δt of 50 s. The feedback signal is reported in Figure 6 as well. It is possible to notice that the average power output from the sorption heat pump during an overall can be adjusted with this strategy. Furthermore, as confirmed by Figure 7, the proposed approach is able to keep the temperature level delivered to the user close to the target, thus properly operating the adsorption machine. It will be then proposed for the implementation in the prototype to be tested in the lab and then in the demo sites for the GEOFIT project.

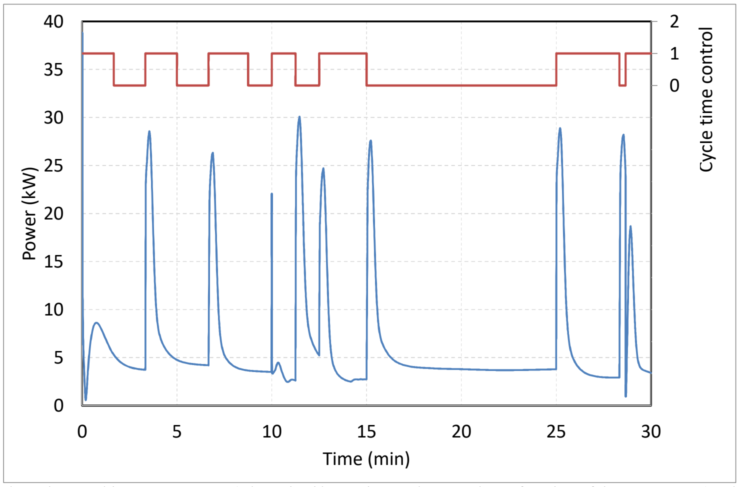

Figure 6: Adsorption machine output power (adsorption/desorption cycle control as a function of the temperature)- The red line indicates the feedback signal based on $T_{user,measured}$-$T_{user,set}$

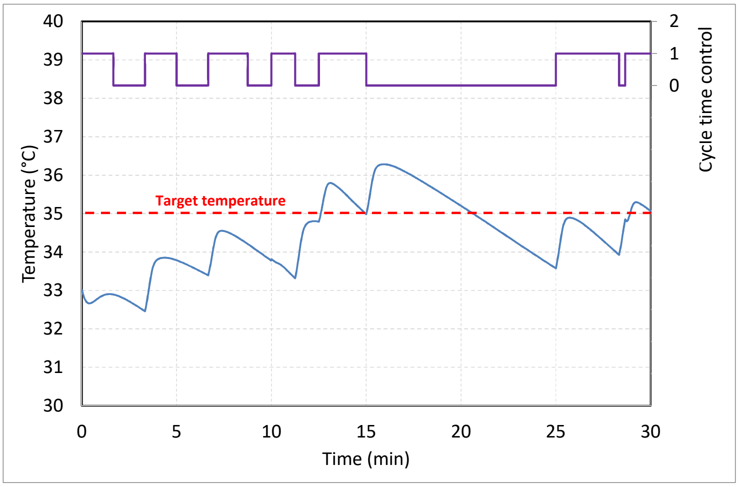

Figure 7: Temperature of the water delivered to the user using the feedback control

6. Conclusions and future activities

The present paper presents the modelling activity of a novel hybrid sorption concept for retrofitting of heating systems in existing buildings, using a gas-driven sorption heat pump and a ground-source HEX as heat source for evaporation. A dynamic model in Dymola was implemented, including a black-box model of the gas boiler, as well as a detailed adsorption module which comprises heat and mass transfer mode as well as equilibrium data for the given zeolite/water working pair. Particular focus was put on control and management strategies for the system, evaluating the flexibility of the heat pump with variable load and temperature conditions. The best control strategy identified is based on the continuous variation of cycle time according to a feedback control on delivered temperature to the user. As shown in Figure 8, the next steps will include model validation thanks to results from laboratory activity, as well as the definition of an improved design and its adaptation to the pilot sites for the project.

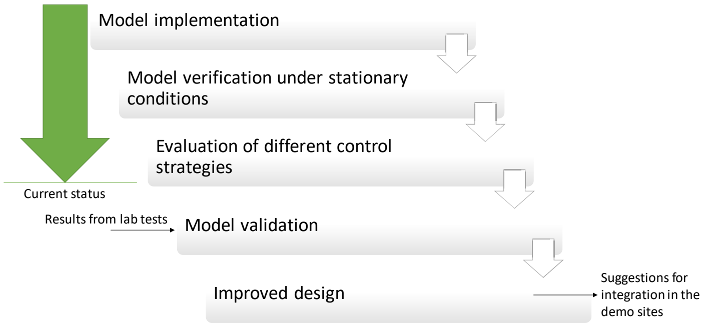

Figure 8: Model development and future steps.

Acknowledgements

This work was funded by the project Geofit: Deployment of novel GEOthermal systems, technologies and tools for energy efficient building retroFITting, which has received funding from the European Commission H2020 Programme under Grant Agreement No. 792210

References

[1] European Commission, COM(2016) 51 final: An EU Strategy on Heating and Cooling | Build Up, (2016). http://www.buildup.eu/en/node/47833 (accessed February 8, 2019).
[2] S.J. Self, B. V. Reddy, M.A. Rosen, Geothermal heat pump systems: Status review and comparison with other heating options, Appl. Energy. 101 (2013) 341–348. doi:10.1016/J.APENERGY.2012.01.048.
[3] D. Antonijevic, M. Komatina, Sustainable sub-geothermal heat pump heating in Serbia, Renew. Sustain. Energy Rev. 15 (2011) 3534–3538. doi:10.1016/J.RSER.2011.05.008.
[4] B. Morrone, G. Coppola, V. Raucci, Energy and economic savings using geothermal heat pumps in different climates, Energy Convers. Manag. 88 (2014) 189–198. doi:10.1016/J.ENCONMAN.2014.08.007.
[5] A. Cetin, Y.K. Kadioglu, H. Paksoy, Underground thermal heat storage and ground source heat pump activities in Turkey, Sol. Energy. (2019). doi:10.1016/J.SOLENER.2018.12.055.
[6] H. Yousefi, H. Ármannsson, S. Roumi, S. Tabasi, H. Mansoori, M. Hosseinzadeh, Feasibility study and economical evaluations of geothermal heat pumps in Iran, Geothermics. 72 (2018) 64–73. doi:10.1016/J.GEOTHERMICS.2017.10.017.
[7] Y. Chang, Y. Gu, L. Zhang, C. Wu, L. Liang, Energy and environmental implications of using geothermal heat pumps in buildings: An example from north China, J. Clean. Prod. 167 (2017) 484–492. doi:10.1016/J.JCLEPRO.2017.08.199.
[8] J. Molavi, J. McDaniel, A Review of the Benefits of Geothermal Heat Pump Systems in Retail Buildings, Procedia Eng. 145 (2016) 1135–1143. doi:10.1016/J.PROENG.2016.04.147.
[9] Geofit project, (n.d.). http://geofit-project.eu/.
[10] J. Choi, B. Kang, H. Cho, Performance comparison between R22 and R744 solar-geothermal hybrid

heat pumps according to heat source conditions, Renew. Energy. 71 (2014) 414–424. doi:10.1016/J.RENENE.2014.05.057.
[11] D.P. Zurmuhl, M.Z. Lukawski, G.A. Aguirre, W.R. Law, G.P. Schnaars, K.F. Beckers, C.L. Anderson, J.W. Tester, Hybrid Geothermal Heat Pumps for Cooling Telecommunications Data Centers, Energy Build. (2019). doi:10.1016/J.ENBUILD.2019.01.042.
[12] L.I. Lubis, M. Kanoglu, I. Dincer, M.A. Rosen, Thermodynamic analysis of a hybrid geothermal heat pump system, Geothermics. 40 (2011) 233–238. doi:10.1016/J.GEOTHERMICS.2011.06.004.
[13] P.A. Fritzson, Introduction to Modeling and Simulation of Technical and Physical Systems with Modelica by Fritzson, Peter A., John Wiley & Sons, Inc, Hoboken, New Jersey, 2011. http://www.amazon.de/Introduction-Simulation-Technical-Sep-30-2011-Paperback/dp/B009KJBU2O/ref=sr_1_1?s=books&ie=UTF8&qid=1376394696&sr=1-1&keywords=fritzson+2011.
[14] Modelica Association, Functional Mock-up Interface, (n.d.). https://fmi-standard.org/ (accessed July 30, 2019).
[15] V. Palomba, E. Varvagiannis, S. Karellas, A. Frazzica, V. Palomba, E. Varvagiannis, S. Karellas, A. Frazzica, Hybrid Adsorption-Compression Systems for Air Conditioning in Efficient Buildings: Design through Validated Dynamic Models, Energies. 12 (2019) 1161. doi:10.3390/en12061161.
[16] Fahrenheit zeolite products, (n.d.). https://fahrenheit.cool/en/zeolite-technology/.
[17] S. Vasta, V. Brancato, D. La Rosa, V. Palomba, G. Restuccia, A. Sapienza, A. Frazzica, S. Vasta, V. Brancato, D. La Rosa, V. Palomba, G. Restuccia, A. Sapienza, A. Frazzica, Adsorption Heat Storage: State-of-the-Art and Future Perspectives, Nanomaterials. 8 (2018) 522. doi:10.3390/nano8070522.
[18] A. Sapienza, V. Palomba, G. Gullì, A. Frazzica, S. Vasta, A new management strategy based on the reallocation of ads-/desorption times: Experimental operation of a full-scale 3 beds adsorption chiller, Appl. Energy. 205 (2017) 1081–1090. doi:10.1016/j.apenergy.2017.08.036.