Taylor & Francis
Taylor & Francis Group

Science and Technology for the Built Environment

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/uhvc21

Environmental and energy performance assessment of hybrid ground source heat pump coupled with TABS emission system in the EU non-residential building typologies

Rana Mahmoud, Mohsen Sharifi, Eline Himpe & Jelle Laverge

To cite this article: Rana Mahmoud, Mohsen Sharifi, Eline Himpe & Jelle Laverge (2022) Environmental and energy performance assessment of hybrid ground source heat pump coupled with TABS emission system in the EU non-residential building typologies, Science and Technology for the Built Environment, 28:10, 1312-1328, DOI: 10.1080/23744731.2022.2073103

To link to this article: https://doi.org/10.1080/23744731.2022.2073103

Published online: 25 May 2022.

Science and Technology for the Built Environment, (2022) **28**, 1312–1328

ISSN: 2374-4731 print / 2374-474X online
DOI: 10.1080/23744731.2022.2073103

Environmental and energy performance assessment of hybrid ground source heat pump coupled with TABS emission system in the EU non-residential building typologies

RANA MAHMOUD*, MOHSEN SHARIFI, ELINE HIMPE, AND JELLE LAVERGE

Research Group Building Physics, Faculty of Architecture and Engineering, Ghent University, Ghent, Belgium

Hybrid Ground Source Heat Pump (GSHP) coupled with radiant emission system is a storage-integrated renewable HVAC technology. Previous attempts that assessed the potential of such a system either employed steady-state estimates or were limited to a few cases. However, incorporating system and building dynamics is crucial to accurately estimate the GSHP's share in the total final energy delivered to the building, hence its energy performance. This paper assesses the environmental and energy performance of the system in non-residential building typologies in the EU. It provides a robust quantification of its potential in the building sector's clean energy transition. We developed an automated method employing dynamic models to estimate building thermal loads. Parametric archetypes were developed to represent the diverse characteristics of the EU non-residential building stock. The analysis of 94,000 cases showed that the storage-integrated hybrid GSHP system covers more than 50% of the annual energy demand in 55% of the cases. The system reduced annual median primary energy and CO_2 emissions by half compared to conventional systems, reaching 25 kWh/(m^2.a) and 5 kgCO_2/(m^2.a), respectively. These results suggest that a significant reduction in CO_2 emissions is achievable by implementing storage-integrated hybrid GSHP in the EU non-residential buildings.

Introduction

In 2021, the European Commission announced the Fit for 55 ambitious policy package to align all sectors to achieve CO_2 emissions reduction of 55% by 2030 as part of the green deal (European Commission 2020). Deployment of innovative heating and cooling technologies on a wide scale of buildings is crucial for realizing these goals, as the International Energy Agency final report emphasized (IEA 2021).

A Ground Source Heat Pump (GSHP), also referred to as a geothermal heat pump, is a renewable, high-performance, all-electric HVAC solution. GSHP can reduce heating and cooling energy consumption as well as carbon emissions from buildings by up to 66% when compared to a conventional fossil fuel based HVAC system (Self, Reddy, and Rosen 2013; Mustafa Omer 2008; Chua, Chou, and Yang 2010; Guo et al. 2012; Boydens et al. 2013). Thermal Active Building Systems (TABS) are radiative heating and cooling emission systems. The radiative heat transfer properties of TABS help in achieving an even distribution of temperature with limited air movements within the indoor space, thus providing indoor thermal comfort for users (Babiak, Olesen, and Petras 2007; Rhee and Kim 2015). TABS use circulating water in pipes integrated into the building mass (i.e., ceiling, floors) thus, the building acts as thermal storage to charge and discharge heat to and from the indoor space. Load shifting and peak shaving are possible thanks to the TABS thermal storage, thus facilitating the more efficient use of renewables by shifting loads to the moments when renewable energy sources are available (Olesen 2012). The large emission surfaces of TABS enable heating and cooling of the different building zones using temperatures close to room temperature (low water temperature for heating 22-28 °C and high water temperature for cooling 15-22 °C). Thus, the smaller temperature difference between the heat source and the heat sink, leads to a higher coefficient of performance (COP) of the heat pump (Boydens et al. 2013; Sarbu and Sebarchievici 2014). The integration of TABS with the GSHP can significantly downsize the ground heat exchanger (Arghand et al. 2021). This is due to the longer duration TABS need to remove heat from the zone,

Received November 23, 2021; accepted April 28, 2022
Rana Mahmoud, PhD Researcher and Architect Engineer. **Mohsen Sharifi**, PhD Researcher. **Eline Himpe**, Postdoc researcher. **Jelle Laverge**, Assosiate Professor, Member ASHRAE.
*Corresponding author e-mail: rana.mahmoud@ugent.be

lowering peak load and extending the time necessary to inject heat into the ground (Arghand et al. 2021). Combining the GSHP system with TABS, called GEOTABS, is thus, a storage-integrated renewable system that can provide thermal comfort for building users and reduce energy consumption (Boydens et al. 2013).

Despite the benefits of applying (GEOTABS), hurdles to its application in buildings persist. These barriers are related to technical and design problems faced at both the production and the emission sides.

At the production side, a thermal imbalance between the heat injected and extracted from the ground will deteriorate the GSHPs performance (Liu et al. 2017). While at the emission side, TABS require time to transition from heating mode to cooling mode or vice versa due to their large thermal inertia. Thus, for realizing TABS in buildings, designers have to follow strict design criteria (e.g., decreased window to wall ratios, installed shading system, low or fixed internal heat gains) to reduce the sudden shifts between heating and cooling (Meierhans 1996; Peperkamp and Vercammen 2009; Olesen 2012; Park et al. 2014; Boydens et al. 2013). These design constraints narrowed down the implementation of GSHP and TABS to a limited segment of buildings. Coupling an auxiliary heating and cooling system to the production and the emission sides can shift the risk of ground imbalance while providing flexibility for the building design criteria, as well as improve the thermal comfort (Alavy et al. 2013; Nguyen et al. 2014; Allaerts, Coomans, and Salenbien 2015; Liu et al. 2017).

The hybridGEOTABS concept represents these combined solutions. The primary system (GEOTABS) covers the buildings' baseload, while a secondary fast-reacting heating and cooling system are integrated at the production and the emission sides to cover the residual loads (Himpe et al. 2018; 2021). Thus, the capital costs are reduced, the thermal comfort is guaranteed, and, importantly, this low-carbon system can be applied in a large variation of buildings. Furthermore, the operation of this hybrid system is optimized using a Model Predictive Controller (MPC). The MPC ensures that the system components operate efficiently, considering the users' thermal comfort, resulting in energy savings and reductions in the CO_2 emissions of the buildings (Drgoňa et al. 2020).

Quantifying the environmental and energy performance of hybridGEOTABS in a large variation of buildings is, therefore, necessary to better understand its potential applications and role as a possible solution for decarbonizing the building sector.

Identifying gaps in literature

To assess the system performance and evaluate its CO_2 emission reductions on an extensive variation of buildings, a relevant question is, what are the primary system (GEOTABS) shares in the final energy delivered to a given building?

Picard and Helsen (2018) have assessed the CO_2 emission reductions from implementing a hybridGEOTABS solution (GEOTABS coupled with condensing gas boiler (CGB) and an Electric Chiller (EC)). They concluded that the hybridGEOTABS solution is a viable technology that may cut CO_2 emissions by up to 50% compared to a conventional HVAC solution (CGB and EC with a fan coil unit). The study used static calculations to estimate the building thermal loads while assuming fixed shares within the hybrid system's range [0,25,50,75,100%]. Except that, methods based on steady-state estimates to identify the size of the GSHP will only lead to system oversizing and increased investment costs (Spitler and Cullin 2008; Himpe et al. 2021). Moreover, these methods rely on the peak demand, while the cumulative heat injected and extracted from the building over an entire year has a high impact on the net heating and cooling of the geothermal source (Fisher et al. 2006). Therefore, incorporating the system (GEOTABS), and building dynamics to accurately identify the primary system's share is crucial for assessing the potential of such a complex low carbon HVAC solution.

Additionally, studies that evaluated the potential of low carbon technologies such as GSHP on a wide scale of buildings were based on a limited number of cases. For example, Bagdanavicius and Jenkins (2013) used Building Energy Simulation (BES) models to assess the peak heating power demands of 92 dwellings, represented by six models. However, this study considered only two types of dwelling envelope (poorly and highly insulated dwellings). The results were then hypothetically extrapolated to half of the UK's dwellings. Bayer et al. (2012) used a top-down statistical approach to investigate the CO_2 emissions savings in residential buildings with installed GSHPs in 19 European countries. The study looked at space heating demands based on aggregated national statistical data estimates per country. The study estimated savings of 3.5 million tons of CO_2 emissions from the installed GSHP in 2008, and a projection of 5.5 million tons in 2011. However, these studies looked at buildings from a narrowed perspective, without investigating their diverse characteristic (i.e., different typologies, geometry, thermal performance of the envelope, occupancy profiles, glazing percentage, etc.), which influence the system performance and the CO_2 emissions savings.

Furthermore, most of the studies focused on residential buildings, while very few addressed the non-residential ones. This lack of coverage is attributed to the heterogeneity of this sector and the limited data available to characterize it (Economidou et al. 2011; Kohler, Steadman, and Hassler 2009). However, non-residential buildings represent 25% of the building stock in the EU and consume average specific energy of 280 kWh/(m^2.a), which is 40% higher compared to the residential sector (D'Agostino, Cuniberti, and Bertoldi 2017). Additionally, a recent study on the non-residential building stock in England and Wales (The Non-Domestic National Energy Efficiency Data-Framework 2020) found that 60% of the non-residential surface area belongs to buildings with Gross Floor Area (GFA) larger than 1,000 m^2. Besides, they consume more gas and electricity than buildings with a small surface area due to the large area this segment occupies. These reasons strongly motivate our work to shed light on implementing hybridGEOTABS in non-residential buildings for large and mid-size building segments (with GFA $>$ 1,000 m^2).

No previous research evaluated the performance of hybridGEOTABS using dynamic building loads that represent a diverse property of non-residential buildings found in the EU building stock. One factor is a lack of available detailed information for case-by-case modeling of all types of buildings. Another factor is the expensive computational cost of simulating such a large number of complex models with HVAC optimization. As a result, it is important to find a balance between model simplifications and model accuracy.

To this end, this research aims at assessing the energy performance and the environmental impact of hybridGEOTABS across three typologies (offices, schools, and elderly homes) and three Climate zones. This work bridges the gap by providing an automated methodology that estimates the hourly heating and cooling building loads using BES models in Modelica (Modelica 2021). We developed parametric archetypes, which have proved invaluable in representing the diverse variations of the building stock (Delghust 2015). Using this technique, the building geometrical and building physical parameters of selected archetypes are varied. These variations are based on inventories of the properties of large amounts of individual real buildings in the building stock. Thus, covering the diverse building properties found in the building design space within major climates in the EU. The estimated thermal loads of 94,000 cases were then used as an input for a sizing methodology of hybridGEOTABS developed by (Sharifi, Mahmoud et al. 2022a). The sizing method considers the dynamic interaction of the following system components (TABS, MPC, and the building thermal loads). The energy performance and environmental impact of hybridGEOTABS are then assessed against a conventional HVAC system called non-GEOTABS, using primary energy and CO_2 emissions as indicators.

Materials and methods

Building stock modeling techniques

Building stock modeling techniques are widely used to quantify the potential of energy and CO_2 emission reductions in buildings, among other indicators, to inform decision-makers. The bottom-up building stock approach can capture the level of details needed to identify the impact of modifying building components on energy reductions at an individual building scale. The representation of the buildings stock by selecting archetypes is one of the bottom-up modeling techniques (G. Swan and Ugursal 2009). The choice of the number of archetypes depends on the research question, available data, and computational cost. Ballarini, Corgnati, and Corrado (2014), in the TABULA project, modeled a few archetypes (between 6 and 27 archetypes per country) to estimate the energy savings and CO_2 emission reductions for the European residential building stock. The National Renewable Energy Laboratory (NREL) developed large-scale models such as the ComStock (ComStock Analysis Tool 2021) and the ResStock (ResStock Analysis Tool 2017), covering different variations of commercial and residential buildings archetypes in the USA. Wilson et al. (2017) have used the ResStock model implementing 350,000 archetypes simulations to assess the energy efficiency and economic potential of single-family detached housing in the USA deploying high-performance computing.

Using a limited number of archetypes can be a solution to limit the computational cost. However, it can overlook the geometrical and building physical variations that characterize the building design space. Whereas high-performance computing can overcome this problem, it is not always easily accessible. Delghust (2015) used parametric archetypes, using simplified quasi-steady state multi-zone models to assess the energy savings of 15,000 houses extracted from the Flemish EPBD database. He showed that an archetype representation is rather good to reproduce the distribution on stock level using only basic geometric properties like volume and heat loss area from the original cases in the EPBD database. In this parametric approach, the geometrical data gathered from the building stock and building physical parameters of the archetypes are combined, resulting in a large sample of building cases. Thus, by adopting a parametric archetype modeling approach, we can explore the design space using few available data, with lower computational costs, to investigate the applicability of hybridGEOTABS technology in the EU buildings.

Heating and cooling demand estimation methodology

The methodological framework is divided into eight steps, as demonstrated in Figure 1. First, we gathered a sample of individual building geometrical data. The data describes building volume (GFA), compactness, and heat loss area, representing the geometrical variations possibly found in the EU stock. These data could be collected if available from several sources such as EPBD national databases, building energy performance certificates, and building registries. A characterization of typology follows this step. Thus, floor plans were analyzed for each building type to derive a representative multi-zone archetype that describes the typical layouts, sizes, and functions of the different zones in the respective typologies. Next, the geometrical fitting and parametrization process is applied to the building stock data. Subsequently, the building geometry is defined by its dimensions, which are functions of the building surface area, volume, and heat loss area, input from the building stock data sample. Then, a basic geometrical form (archetype), as shown in Figure 2, is scaled and stretched to fit the geometric parameters of a specific building. At the same time, the archetype form has to respect the constrained dimensions of the spaces following the typology characterization step.

After fitting the outer building form, multi-zone floors are defined based on assigning different zones constrained by the areas of the external and internal walls. Next, Python code is developed to create an output file and feed it into the BES models. Each of the building geometries (output from the previous steps) was combined with different building physical properties, as summarized in Figure 2. Three

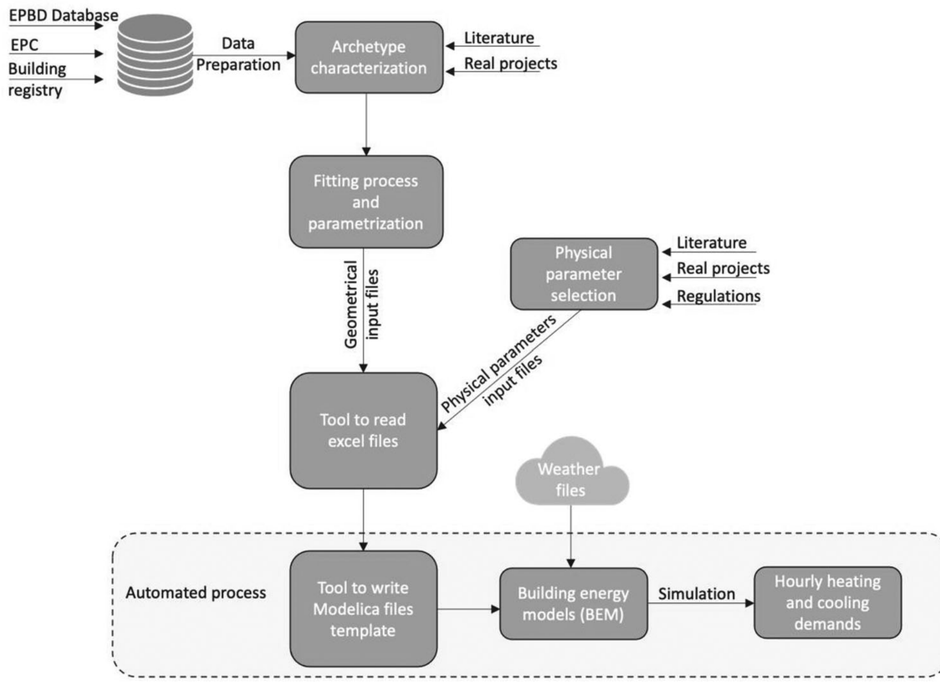

Fig. 1. Building stock bottom-up modeling methodological scheme.

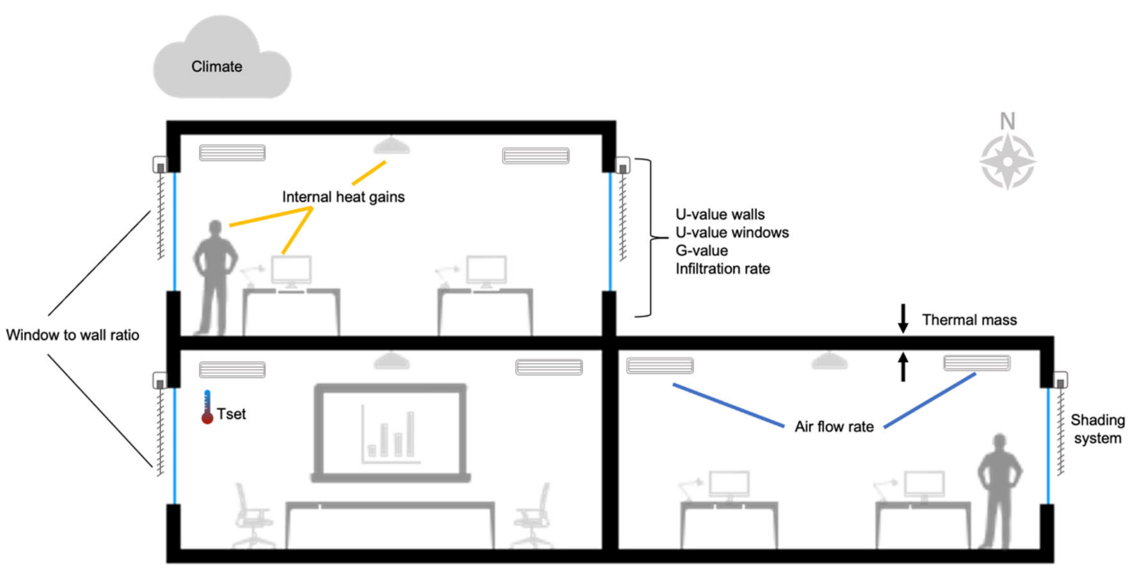

Fig. 2. Building archetype and the parameters that are varied to define the building design space.

climatic zones (Warsaw, Brussels, and Madrid) were chosen to represent the variations in the EU climates, as illustrated by Mahmoud, Himpe et al. (2021a). The climate zones were chosen based on (a) population density, an indicator for building density, and (b) following the climate zones division of the European Environment Agency (EEA) (EEA 2012). Low population density regions, such as those located in "transitional cold" climates, are not considered, as the population density in these regions is less than 50 inhabitants per km^2.

BES models are created using Modelica modeling language (Modelica 2021), in the Dymola program (Dymola 2018) and applying the OpenIDEAS library (Baetens et al. 2015). For each archetype, a multi-zone BES model is created. The Multi-zone BES model is a key in this work to represent the different functions needs and occupancy profiles. Thus, capturing the influence of varying the heat gains profiles on the hourly energy demands. Thus, each floor model has a range between 5 and 8 zones depending on the functions per typology.

We used an ideal heating system modeled with fixed temperature setpoints dependent on the typology characteristics. The ventilation system has a heat recovery of 85% efficiency and a flow rate depending on occupancy schedules. A more generic multi-zone modeling approach is deployed to reduce the simulation time, assuming that all the building slabs have TABS installed. Hence, in this model, the connecting slabs between floors are thermally separated (adiabatic) with no heat transfer. The modeling approach (adiabatic) was validated for an office building case, compared to a detailed model with a higher level of details. The detailed model had a 15% higher total energy demand than the generic model. However, the hourly heating and cooling demands of both models were in a very good agreement as documented by Mahmoud et al. (2019a). The generic model succeeded to reduce the simulations time by 80% compared to a non-adiabatic detailed model.

The simulation process of all models was automated using python in combination with Modelica. Each output file contains a one-year hourly heating and cooling demand as input for sizing the hybridGEOTABS and non-GEOTABS HVAC system scenarios, as explained in the following section.

hybridGEOTABS sizing

hybridGEOTABS system shares are identified by using an Optimal Load Splitting Algorithm (OLSA) developed by (Sharifi et al. 2019; Sharifi, Mahmoud et al. 2022a)). The algorithm splits the hourly heating and cooling thermal loads estimated by the BES model, into loads covered by GEOTABS (primary system) and the residual loads covered by the fast-reacting (secondary) system using an optimization function. The algorithm uses a surrogate model of the building and TABS to simulate their dynamic thermal behavior. The algorithm includes a near-optimal controller and has a built-in optimization algorithm that allows to optimally split the loads and maintain thermal comfort in the building, as documented by (Sharifi, Mahmoud et al. 2022a). For the TABS model, pipes are embedded in the ceiling at a depth of 100 mm from the lower surface and 140 mm from the upper surface of the slab. The pipes have a diameter of 20 mm, and the distance between them is 150 mm. TABS are assumed to cover 80% of the total conditioned surface. More details regarding the TABS model assumptions are summarized in Mahmoud et al. (2022).

The OLSA allows an indoor temperature that fluctuates ± 1 °C from the used operational temperature in the BES models considering thermal comfort. These fluctuations in indoor temperature combined with the thermal inertia of the TABS allow the load shifting and peak shaving behavior that is optimized using a near-optimal control system. By identifying the shares of each system in the previous step, the sizing of the hybridGEOTABS components takes place using a postprocessing step documented by Sharifi et al. (2021). In this step, a thermal balance constraint for the borefield and its effect on the sizing of the hybridGEOTABS system is introduced. Previous studies (You et al. 2017; Wu et al. 2014) have shown that the thermal imbalance between heating and cooling loads of the borefield can adversely affect its efficiency in the long term. Furthermore, (Sharifi et al. 2022b) demonstrated that increasing the borefield length to compensate for thermal imbalance is financially inefficient. Additionally, they demonstrated that the borefield can efficiently deal with a limited amount of borefield imbalance. Accordingly, we assumed that the building's annual heating or cooling loads could not be higher than 60% or lower than 40% of the total annual load of the building. We consider this (40-60) rule as a 'safe' assumption to ensure that the borefield does not get depleted, and passive cooling can be used in moderate and cold climates. Due to the complexity of modeling the distribution system (water circulating pump), we opted for assuming a Seasonal Performance Factor (SPF) for the GSHP while including the energy use of the production system. The underlying assumption is that the distribution system is appropriately designed to deliver the heat with a given loss to the different building zones based on their demands.

hybridGEOTABS energy performance and environmental impact assessment

A baseline scenario "non-GEOTABS" representing the use of conventional heating and cooling systems and a "hybridGEOTABS" scenario are compared in terms of energy performance and CO_2 emissions. In the non-GEOTABS scenario, heating demands are covered by (CGB), whereas cooling demands are covered by an (EC), and all heating and cooling are injected as convective heat fluxes in the space. For the hybridGEOTABS scenario, TABS are coupled to the GSHP for active heating and active cooling or with a heat exchanger for passive cooling covering the baseload as shown in Figure 3, and the residual demands are covered by two conventional secondary systems CGB for heating and an EC for cooling. For the "hybridGEOTABS" scenario, we assumed that all the cooling energy covered by the baseload could be provided using passive cooling for cold and moderate climate zones. Thus, the TABS absorbs the heat from the building and transfers it to the borefield via a heat exchanger, bypassing the heat pump (Boydens et al. 2013). This assumption is attributed to the low undisturbed temperature of the ground during the long period of the year in temperate and cold climates such as Warsaw and Brussels locations, which allows for passive cooling. Whereas, for the warm climate, a reversible heat pump provides the cooling energy baseload.

The final energy is calculated by dividing the heating and cooling energy demand covered by each production system with its efficiency, as summarized in Table 1. The production efficiencies in Table 1 are assumed to be fixed values. Assuming a variable temperature-dependent SPF will require a detailed model of the heat pump, increasing the mathematical complexity and the computational time for such a large scale of simulations. The SPFs values assumed are based on datasheets from manufacturers of GSHP. The passive cooling coefficient of performance is assumed based on REHVA Guidebook no.20 (Boydens et al. 2013), which suggests a range of 10 to 30; thus, we considered a fixed value within this range.

The primary energy is then calculated by multiplying the final energy depending on the production source by its related primary energy conversion factor for either electricity or gas

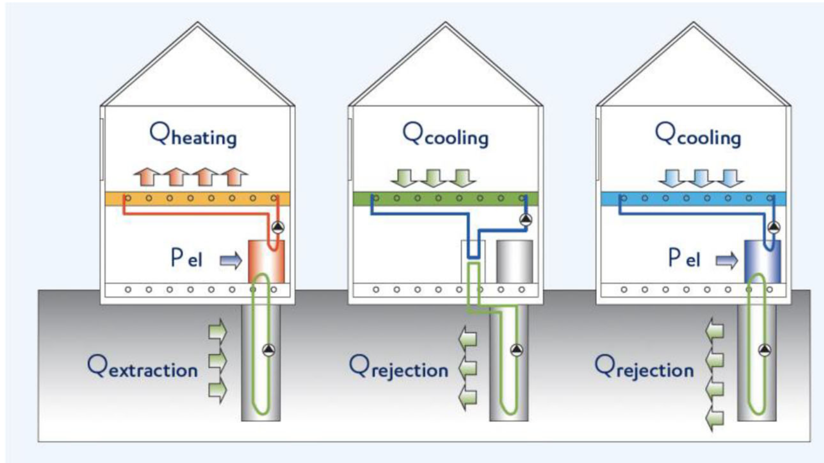

Fig. 3. GEOTABS concept in heating (left), passive cooling (center) and active cooling (right), source: (Verhelst 2012).

Table 1. Production efficiencies for the different systems.

Type of production unit	efficiencies
Heat pump (heat production) SPF	6.00
Heat pump (Cold production) SPF	5.00
Gas boiler (heat production) μ	0.95
Electric chiller (Cold production) EER	3.00
Passive cooling (Cold production)	20.00

(see Table 2). To calculate the CO_2 emission for each scenario, we multiplied the final energy depending on the amount of gas and electricity the building takes from the grid based on the production source and its CO_2 emission conversion factor (Table 2). Finally, each system's total CO_2 emission from heating and cooling is summed up for each case.

Implementation of the methodology on non-residential typologies

Three non-residential typologies, namely offices, schools, and elderly homes, are used to demonstrate the methodology illustrated in Figure 1. The geometrical data input was gathered from the Flemish energy agency (VEA) (VEA-EPB database 2016) for office and schools building typologies. This database was collected to perform building energy certifications. The elderly homes stock data is a random sample collected as an output of a building stock model that is provided with data from the Swiss building registry (Bundesamt für Statistik 2018). The data gathered for all three typologies contains general geometrical data such as building gross volume, GFA, heat loss surface area, and building compactness presented in Figure 4. Building compactness is defined as the ratio of the conditioned volume to the sum of the building heat loss areas, including ground and roof. Compactness is used as an indicator to measure the influence of building shape on the heat gains or losses; thus, the heating and cooling demands as discussed in the study by Catalina, Virgone, and Iordache (2011). The gathered geometrical sample accounts for 279 offices, 116 schools, and 20 elderly homes. The sample of building geometrical input used in this work relies on a selection of cases due to the lack of information at a high level of granularity per EU country. Therefore, it is not a representative distribution of the geometries of the whole EU building stock. Nevertheless, it gives a good indication of the typical design space of the selected typologies in the EU.

Energy-related parameters used for all the typologies are summarized in Table 3. The parameters illustrated in Figure 2 are varied for each typology within the three chosen climates considering the following:

- Envelope thermal performance values are based on observation of regulations in various countries, representing high (requirements for a passive building), medium (regulation in a whole range of countries today), and low (mainly applicable in some southern EU regions, but also representative of (older) low-insulated buildings).
- Window to wall ratios: three values are chosen based on the range of ratios used in these typologies.
- Internal gain profiles summarized here are based on more detailed and dynamic occupancy schedules as presented by Mahmoud et al. (2021b).
- Thermal mass is divided into heavyweight (concrete is used in the whole structure) and lightweight (internal walls and part of the slabs are from timber, and the rest in concrete) building construction to represent the variations in buildings found in different regions.
- The shading system represents two variations, the first includes an external shading system which is on when the solar irradiation on vertical windows reaches 150 W/m^2, and the second, no shading system is installed.
- Building orientation: two orientations, west and south, were chosen to see the influence of changing orientation for the larger facade on the energy demand due to solar irradiation.

For each typology, a parametric archetype was created, as summarized in the next paragraphs. Building physical

Table 2. Primary energy conversion factors and CO_2 emissions factor.

	PE Total (-)	FCO_2 emissions (g/kWh)
Natural Gas	1.1 (ISO 52000–11 2017)	220 (ISO 52000–11 2017)
Electricity EU 2020	2.0 (Hamels 2021)	260 (Hamels 2021)

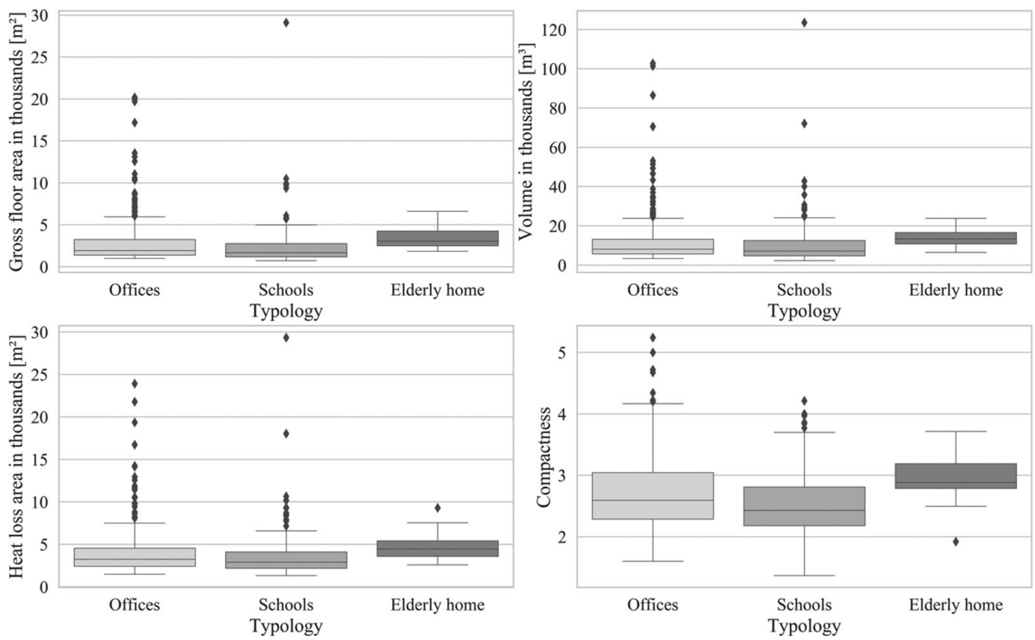

Fig. 4. Geometrical data input distribution per typology.

properties from Table 3 are combined with the variations in building geometrical properties presented in Figure 4. This resulted in 40,000 office cases, 50,000 school cases, and 4,000 elderly homes cases. The load splitting algorithm was then applied to the simulated heating and cooling demand curves for all 94,000 cases outputs, followed by implementing the energy performance and the environmental assessment.

Office building typology

Office buildings are often designed as a modular typology, where offices are distributed around corridors or blocks with meeting rooms and service functions (e.g., copy rooms) from both sides. An average depth for offices is between 4.5 m and 6 m to allow for the use of daylighting (Neufert and Neufert 2000). This typology typically is a multi-story building with less than ten floors or high-rise office buildings with more than ten floors. The typical functions of the zones found in this typology and shares of the different functions are summarized in Table 4. We assumed that the offices have a minimum depth of 6 m, with two up to ten floors. The presented archetype in this work does not account for parking spaces, server rooms, and courtyards since they are unheated areas. The assumptions and function shares are used as constraints for archetype parametrization, which is the basis for the multi-zone BES model.

Schools building typology

Schools' architectural plans were analyzed from the Flemish "Scholen Bouwen" database (Scholenbouwen 2019). The floorplans mostly exhibited modular forms, where classrooms and main functions are distributed along a central corridor from both sides or along a central courtyard with one corridor. The school's typical functions are classrooms, student restaurants, multipurpose rooms (such as library, study room, event room), administration offices, services including toilets, and circulation. Sports rooms and basements are excluded from the GFA since they are not conditioned or conditioned differently. We summarized the share of each function from the GFA in Table 5. From the analysis, we concluded that the average classroom surface area is around 48 m^2 (6×8 m), the minimal width of the corridors is two meters, and the number of floors ranges between one and five. The school archetype characteristics are used as constraints for the geometrical fitting process. The geometrical data are fitted to a modular plan, with a central corridor where functions are distributed on both sides.

Elderly homes typology

Based on the work of Holvoet (2019), a number of 13 elderly home projects located in Belgium were analyzed. He defined three types of archetypes of elderly homes: linear archetype, courtyard archetype and a combination of both. The bedrooms are modularly spread either along one

Table 3. Summary of the parameter's assumptions for the archetype's models.

Parameters			Office building	School building	Elderly home
Window to wall ratio	Lower value		20%[a]	20%	20%
	Average value		40%	40%	35%
	Upper value		60%	60%	50%
Orientation (large facade)	Lower value		South	South	South
	Upper value		West	West	West
Shading System	Lower value		No-Shading	No-Shading	No-Shading
	Upper value		External screen is on at 150 (W/m^2)	External screen is on at 150 (W/m^2)	External screen is on at 150 (W/m^2)
Envelope performance	lower value	Envelope U-value	0.5 ($W/m^2.K$)	0.5 ($W/m^2.K$)	0.5 ($W/m^2.K$)
		Window U-value	2.5($W/m^2.K$)	2.5($W/m^2.K$)	2.5($W/m^2.K$)
		Glass g-value	0.60	0.60	0.60
		airtightness n50	5.0 (h^{-1})	5.0 (h^{-1})	5.0 (h^{-1})
	Average value	Envelope U-value	0.27 ($W/m^2.K$)	0.27 ($W/m^2.K$)	0.27 ($W/m^2.K$)
		Window U-value	1.5 ($W/m^2.K$)	1.5 ($W/m^2.K$)	1.5 ($W/m^2.K$)
		Glass g-value	0.56	0.56	0.56
		airtightness n50	2.0 (h^{-1})	2.0 (h^{-1})	2.0 (h^{-1})
	Upper value	Envelope U-value	0.15 ($W/m^2.K$)	0.15 ($W/m^2.K$)	0.15 ($W/m^2.K$)
		Window U-value	0.8 ($W/m^2.K$)	0.8 ($W/m^2.K$)	0.8 ($W/m^2.K$)
		Glass g-value	0.40	0.40	0.40
		airtightness n50	0.6 (h^{-1})	0.6 (h^{-1})	0.6 (h^{-1})
Building mass	Lower value		390 (kg/m^2)	391 (kg/m^2)	392 (kg/m^2)
	Upper value		630 (kg/m^2)	630 (kg/m^2)	630 (kg/m^2)
Internal heat gains[b]			Office zone	Classroom Zone	Elderly room zone
	Lower value	Density	1Person/20m^2	1Student/3.5m^2	___
		Occupancy	5.0 (W/m^2)	21.0 (W/m^2)	0
		Lighting	8.0 (W/m^2)	8.0 (W/m^2)	0
		Appliances	5.5 (W/m^2)	4.0 (W/m^2)	0
		Total	18.5 (W/m^2)	33.0 (W/m^2)	0
	Upper value	Density	1Person/10m^2	1Student/2.5m^2	1Elderly/24m^2
		Occupancy	10.0 (W/m^2)	30.0 (W/m^2)	3.0 (W/m^2)
		Lighting	8.0 (W/m^2)	8.0 (W/m^2)	4.5 (W/m^2)
		Appliances	15.0 (W/m^2)	4.0 (W/m^2)	4.0 (W/m^2)
		Total	33.0 (W/m^2)	42.0 (W/m^2)	11.5 (W/m^2)
Ventilation flow rate	Based on occupancy		36 (m^3/h)	36 (m^3/h)	50 (m^3/h)
Setpoint temperature	Comfort range		22 – 24 (°C)	22 – 24 (°C)	22 – 24 (°C)

[a]The presented values of the window to wall ratio for office's typology are approximated into three discrete values for simplification. The input values of window to wall ratio for the BES models for office typology were gathered from the building stock database with a minimum of 5% and a maximum of 70% and a median of 30%.

[b]Please note that only one zone is presented here in Table 3 per each typology, the internal heat gains concerning the rest of the other functions per each typology ex. meeting rooms, restaurants, etc., are summarized in (Mahmoud et al. 2021b).

Table 4. Share of office's building typology functions in the floor area excluding walls.

Function (Zone)	*Offices*	*Meeting rooms*	*Restaurant*	*Services and Circulation*
Share in the floor area (%)	60 %	12%	10%	18%

Table 5. Share of school's building typology functions in the floor area excluding walls.

Function (Zone)	*Classrooms*	*Restaurant*	*Multipurpose room*	*Corridors, stairs*	*Administration offices*	*Toilets*
Share in the floor area (%)	40 %	15%	15%	20%	5%	5%

Table 6. Share of elderly home's building typology functions in the floor area excluding walls.

Function (Zone)	*Bedrooms*	*Common living spaces*	*Clinic & offices*	*circulation, elevator & stairs*	*Toilets*
Share in the floor area (%)	50%	20%	6%	18%	6%

circulation corridor or mirrored along the corridor. The archetype is divided into zones called clusters. The clusters are defined by an average of 8 to 20 rooms per cluster. Each has its own common living space as well as toilets. Functions such as outdoor spaces, basement, and parking areas are excluded in the models. The share of the different zones is summarized in Table 6.

The Flemish infrastructure fund for personal affairs (VIPA 2017) has defined the minimum allowed surface area for a single room for elderly homes at 16 m^2 per room, excluding the sanitary area. We assumed a surface area of 24 m^2 (4×7 m) as an average for a resident room, including toilets. Therefore, only one density profile is assumed (no high and low-density) one person per 24 m^2. However, variations to capture the dynamic of residents' activities in elderly homes were implemented using occupancy presence factors that differ during the day (elderly rooms, living areas, clinics, and offices). For more details regarding the occupancy schedules in the different functions, please consult the internal heat gain profiles database published by Mahmoud et al. (2021b).

Other functions such as activity spaces, sitting, and dining areas were combined and named (common living). Corridors are defined with a minimum of 1.80 m to allow for easy access and circulation for the residents.

Results

Heating and cooling energy demand

Heating and cooling demand time series were simulated for a year for ca. 94,000 cases representing three non-residential typologies covering the climate diversity in Europe. The annual heating, cooling, and total demands are shown in Figure 5 per typology and climate zone. The median annual heating demand per floor area (Figure 5a) is lower than 50 kWh/(m^2.a) for all three typologies in the Warsaw and Brussels climates. It is even lower than 15 kWh/(m^2.a) for the Madrid climate. The annual median cooling demand per floor area (Figure 5b) is lower than 25 kWh/(m^2.a) in Warsaw and Brussels climates and about 40 kWh/(m^2.a) in the Madrid climate.

The highest heating demands, above 200 kWh/(m^2.a), are outliers for a few cases in the Warsaw climate with low compactness, low insulated envelope with low air tightness, high window to wall ratio and a shading system. On the other hand, the highest cooling demands, above 150 kWh/(m^2.a), are outliers found in Madrid for cases with medium and high insulated envelope, high window to wall ratio, no shading system installed west oriented buildings, and low compactness.

By observing the annual median total demands, we see that typologies located in Warsaw have the highest median of 77 kWh/(m^2.a) for schools and elderly homes, while for offices, the median total demand is 60 kWh/(m^2.a).

The distribution of the heating to total demand ratios is presented in Figure 6. This ratio is calculated by dividing the heating energy demand by the total energy demand and indicates if the building is heating dominated (ratio $>$ 50%) or cooling dominated (ratio $<$ 50%). From Figure 6, we observe that a higher number of elderly homes and schools' cases are heating dominated, while for office buildings typology, a higher number of buildings are cooling dominated.

Share covered by GEOTABS and geothermal balance

As illustrated in Figure 7, TABS covers at least 80% of the thermal loads in more than 75% of the office building cases, while the fast-reacting secondary system covers the remaining demands. However, the design of GEOTABS depends not only on satisfying the building demands using TABS but also on the amount of heat extracted or injected into the ground along the years of the system operation. Cupeiro Figueroa (2021) found that the borefield can have imbalance but needs to be studied based on a case-by-case assessment, considering environmental constraints and/or legislation. Therefore, a conservative way to approach the minimum share of GEOTABS is implemented in this work, as explained in the "hybridGEOTABS Sizing" section. To this end, by implementing the near balance constraint, higher shares of GEOTABS are found in cases where the heating and cooling loads are more or less in balance. Figure 8 shows the heating to total demand share of the building as a function of the GEOTABS share. The further away the demand is from a balanced situation (for heating/cooling dominant building), the higher the share of the demand covered by the secondary system.

In Figure 9, by plotting the share of GEOTABS using the near balance constraint, it is seen that in most cases, a share of GEOTABS is possible, within the range of 5 and 90%. In 25% of the cases, GEOTABS covers more than 80% of the annual total demand, and for 55% of the cases, it covers more than 50%. Only 4% of the cases have less than 5% share of GEOTABS. Higher shares of GEOTABS are found in buildings located in Warsaw and Brussels and less in Madrid. The different variations in GEEOTABS shares reflect the influence of climate/location on the share of the GEOTAB.

It is observed that the school typology has the highest median share of GEOTABS, which is 70% for Warsaw and Brussels climate. The elderly home typology has the second highest median share ranging from 45% to 65%. The office typology has the lowest shares compared to the other typologies ranging from 38% to 45%, where the lowest median (38%) is found in Madrid.

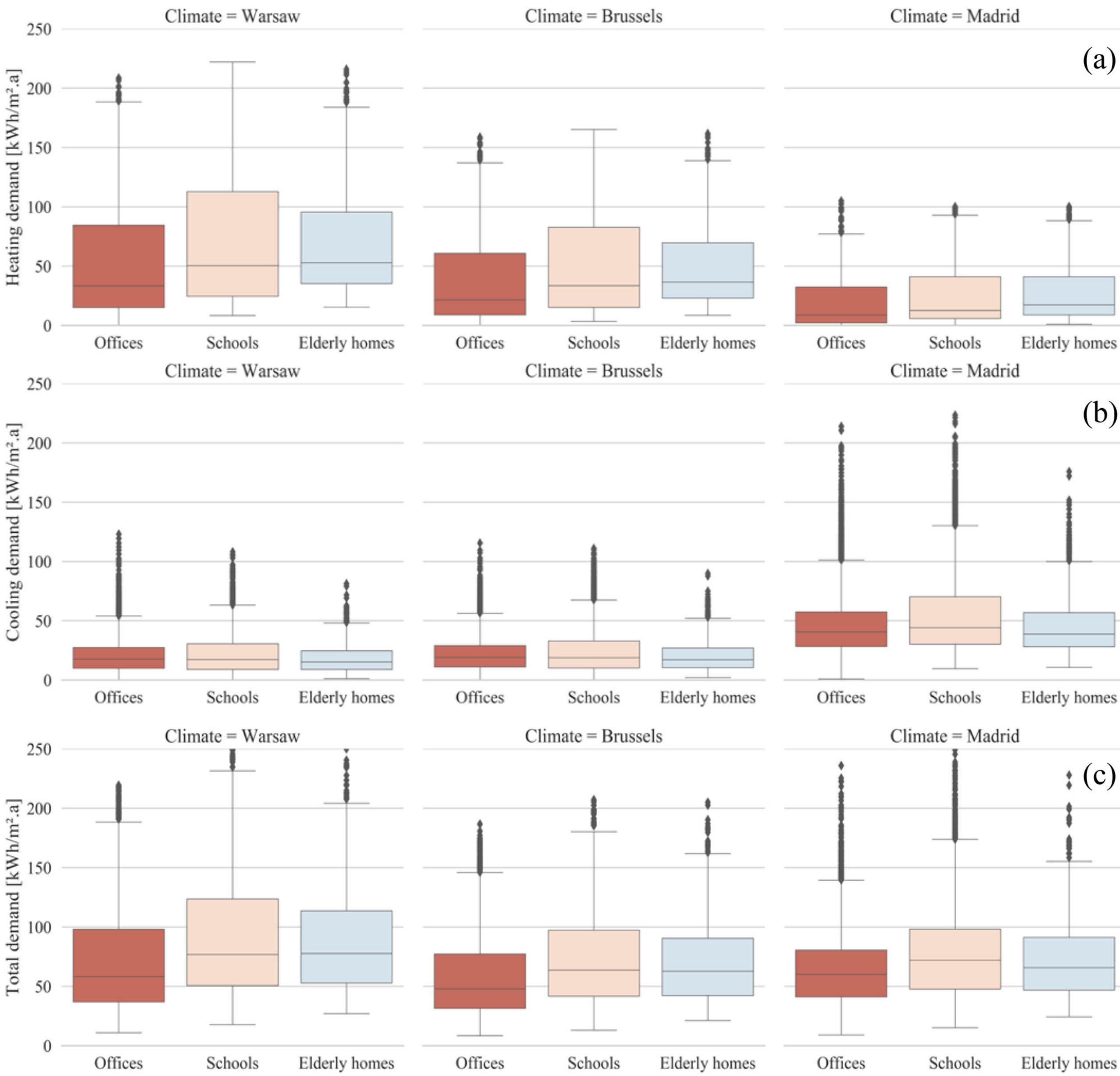

Fig. 5. (a) heating energy demand (b) cooling energy demand (c) total energy demand per floor area, per typology and climate zones.

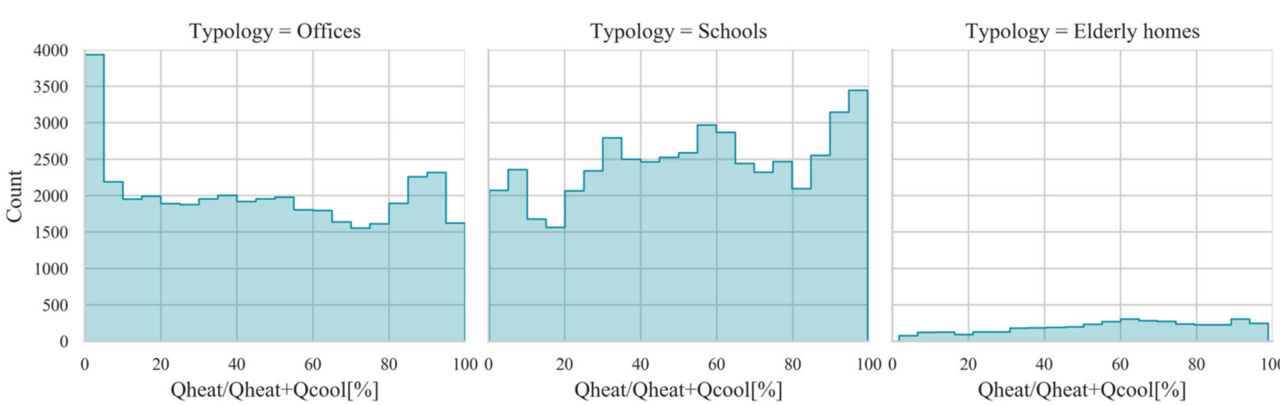

Fig. 6. Comparison between the three typologies in terms of the heating energy demand to total energy demand.

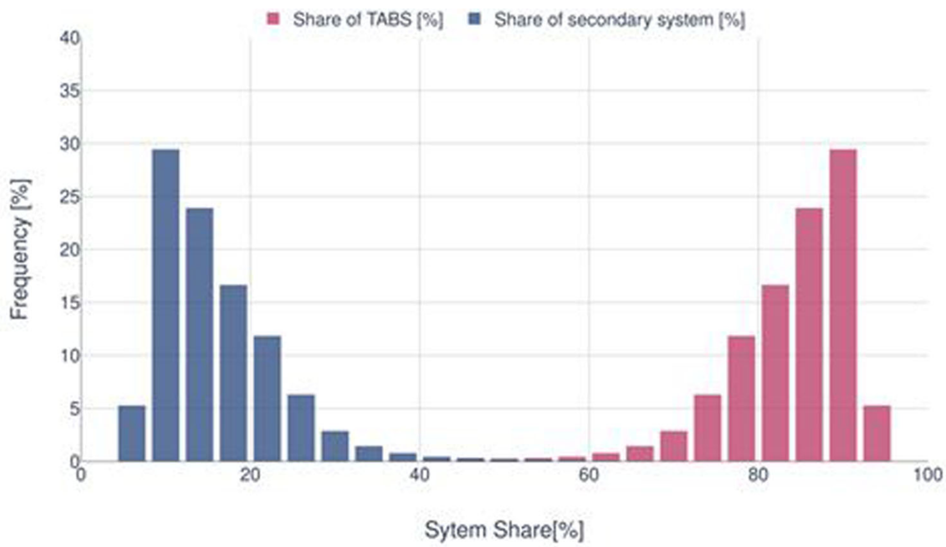

Fig. 7. Distribution of the share of the total energy demand that TABS can cover in the office buildings included in the database.

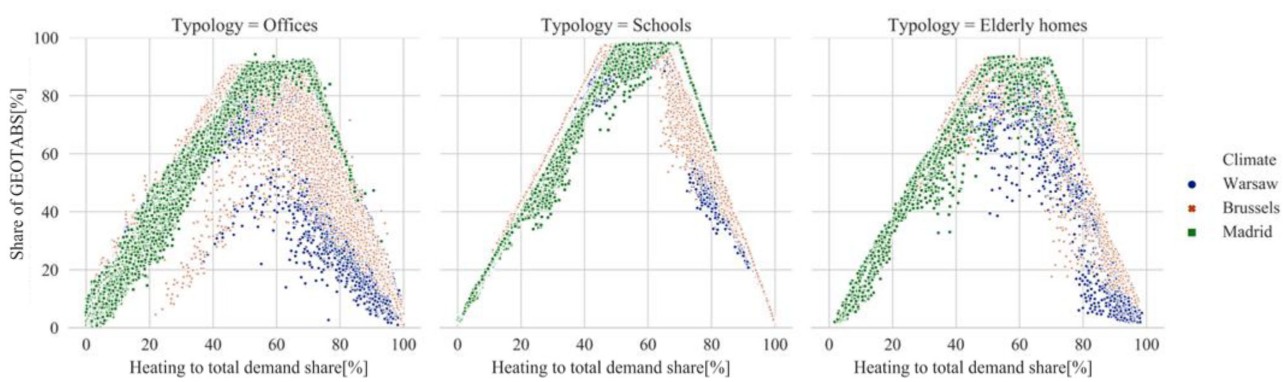

Fig. 8. Relation between the heating to total demand share [%] and the share of GEOTABS [%].

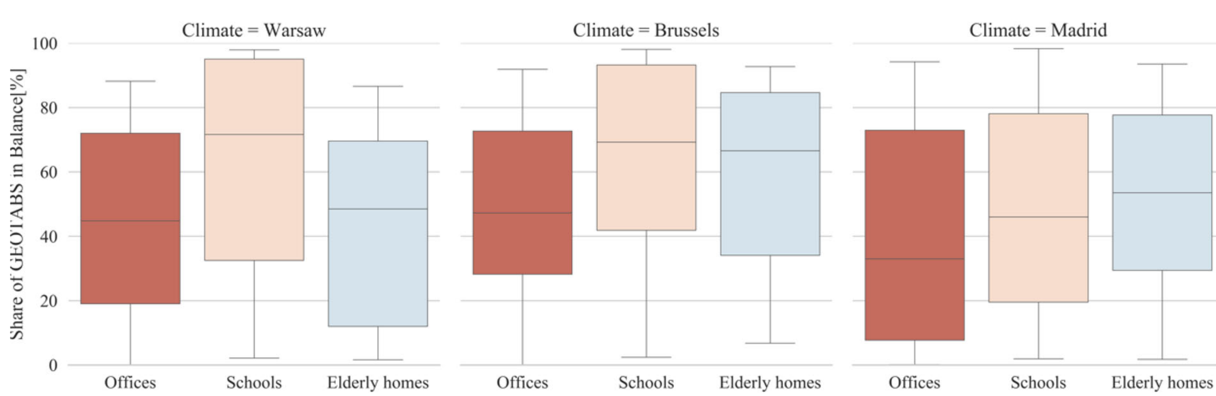

Fig. 9. Share of GEOTABS (%) after applying the balance in the borefield constraint.

Primary energy and CO_2 emissions

Primary energy and CO_2 emissions are used as indicators to investigate the energy saving and environmental potential of the hybridGEOTABS system. A comparison between two HVAC scenarios, hybridGEOTABS, and non-GEOTABS, was implemented for 94,000 cases. In Figure 10, we see that for both primary energy and CO_2 emissions, hybridGEOTABS proves to be more efficient than the non-GEOTABS scenario due to the production system's efficiencies. For the hybridGEOTABS scenario, we see a median primary energy consumption per floor area is 25 kWh/(m^2.a) for all typologies compared to 52 kWh/(m^2.a) for the non-GEOTABS scenario, with median reductions reaching 52%. The lowest primary

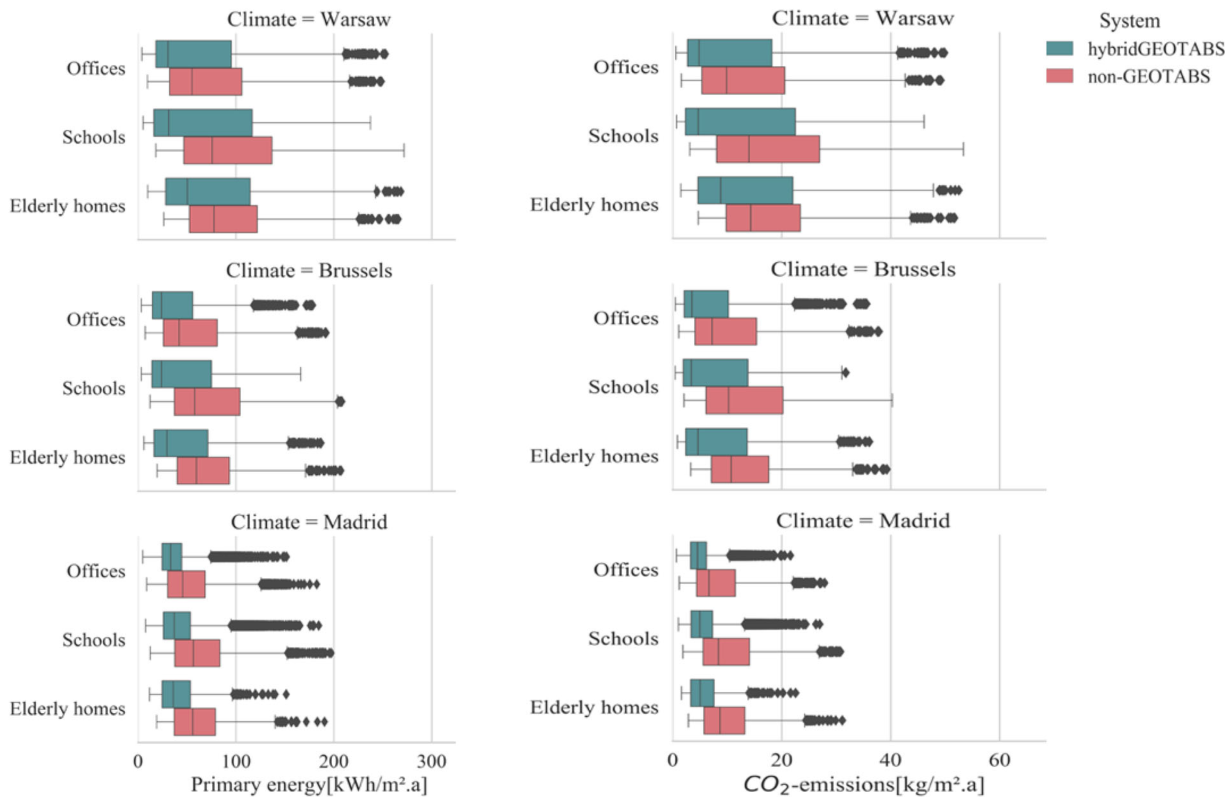

Fig. 10. Comparison between hybridGEOTABS and non-GEOTABS scenarios in terms of (left) the primary energy and (right) the CO_2 emissions of the three typologies divided by climate.

energy consumption per floor area is found in all typologies located in Brussels. In this climate, buildings properties (medium/high insulation) result in a higher balance between heat injected and heat extracted from the borefield, leading to higher shares of GEOTABS. Higher shares of GEOTABS reflect the higher shares of renewables in covering the energy demand, thus lower primary energy.

The CO_2 emissions per floor area are following the same trend, and we see that hybridGEOTABS curbed the median CO_2 emissions by half (50%), reaching 5 $kgCO_2/(m^2.a)$ in comparison to the conventional system, which has a median of 10 $kgCO_2/(m^2.a)$. In terms of overall savings found in the cases as shown in Figure 11, higher primary energy reductions appear in moderate and cold climates and less in the warm climate. The higher reductions are due to replacing the gas boiler with a low efficiency with a more efficient heating system like the GSHP and covering the cooling demand from the primary system with passive cooling in these climates. For the warmer climate, the difference in efficiency between a conventional chiller and GSHP in the cooling mode is lower than the difference between gas boiler efficiency and GSHP in heating mode. The hybridGEOTABS scenario achieved more than 50% CO_2 emissions reductions in 43% of the cases. We observe that the school typology has the highest median primary energy and CO_2 emissions savings in all three climates due to the higher shares of renewables in the hybrid system.

Discussion and perspectives

Parametric archetypes

The modeling approach used in this work (parametrized archetypes) and its reduced simulation time made it feasible to scan the possible design space of non-residential buildings in the EU to investigate hybridGEOTABS potential. Using few available input data, the method succeeded in transforming real building data into BES models to estimate hourly heating and cooling demands of 94,000 buildings covering three major EU climate. The method can be implemented easily on other building typologies, such as multi-family residential buildings as documented by Mahmoud et al. (2019b).

Building stock geometrical data is mostly available in the form of summary statistics. The acquisition of input data at a detailed level for individual non-residential buildings in the building stock is challenging. These challenges are attributed to the limited national databases or national data privacy. However, the methodology presented in this work, using basic geometrical information (gathered from the Flemish EPBD database and the Swiss registry), enriched with energy-related variations gathered from literature, statistics, and regulations succeeded in approximately representing the variations found in the EU non-residential buildings. Making national energy performance certificates, registries, and EPBD databases from EU countries accessible for

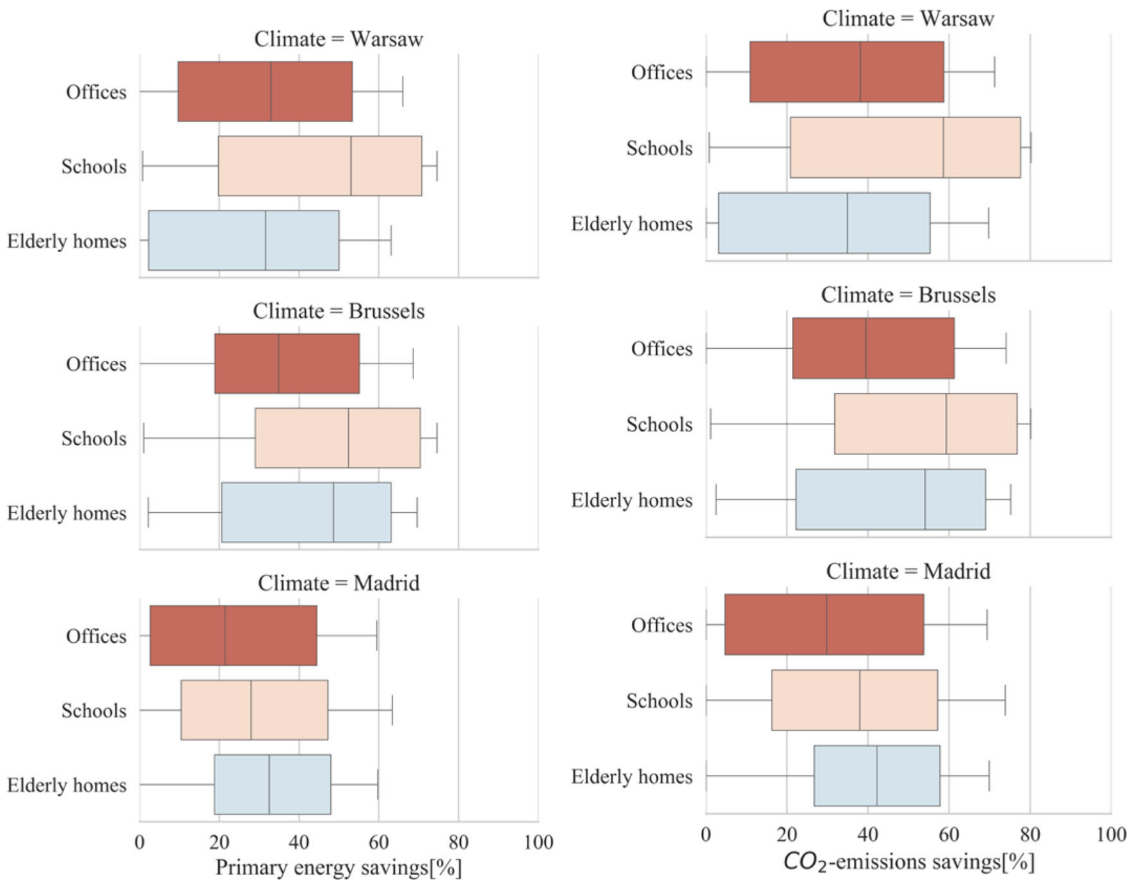

Fig. 11. Savings in (%) achieved from hybridGEOTABS in terms of (left) the primary energy and (right) the CO_2 emissions of the three typologies divided by climate.

research would allow for further investigations on the impact of implementing low-carbon technologies and building retrofitting strategies on the decarbonization of the building stock.

Energy savings and CO_2 emissions reductions using hybridGEOTABS

Complementing GEOTABS with a secondary system has widened its application on a large variety of buildings in the EU compared to what was defined previously by researchers (Meierhans 1996; Peperkamp and Vercammen 2009; Olesen 2012; Park et al. 2014; Boydens et al. 2013). GEOTABS had a share in almost all the studied cases covering the three typologies (offices, schools, and elderly homes) within three major climates in Europe (represented by Warsaw, Brussels, and Madrid). Climate proved to influence the share of the GSHP, which is in agreement with previous studies (Nguyen et al. 2014; Aditya and Narsilio 2020). We observed that the GEOTABS share was lower for cases located in Madrid than in cases located in Warsaw and Brussels. However, hybridGEOTABS can be implemented in all the climates and the studied typologies, even in challenging architectural designs such as buildings with high window to wall ratios, or high internal gains. GEOTABS is thus a low-carbon baseload system that can substitute conventional HVAC systems in buildings in the EU. Even though the presented results demonstrate the 'minimum' share of GEOTABS due to adopting a conservative borefield balance constrain, higher shares are still achievable, based on a case-specific design, where the geothermal balance can be assessed more in detail.

HybridGEOTABS has illustrated high energy and CO_2 emission reductions for non-residential buildings in the EU. These results demonstrate the influence of the share of renewables from (GEOTABS) when coupled with a conventional secondary system. By integrating renewables and energy-efficient systems such as photovoltaic, air-source heat pumps, etc., as a secondary system, more energy reductions and CO_2 emissions are achievable. These reductions would be even more profound in cases where the secondary system share is higher, as in cases where the building is heating, or cooling demand dominated.

In this work, we assumed that the average electricity mix representing the EU for 2020 is 2.0 for the primary energy conversion factor and 260 gCO_2/kWh for the CO_2 emission intensity factor. The results show that a moderately clean electricity mix can cut the median annual primary energy and carbon emissions in hybridGEOTABS buildings by half. However, one must highlight that for countries that have

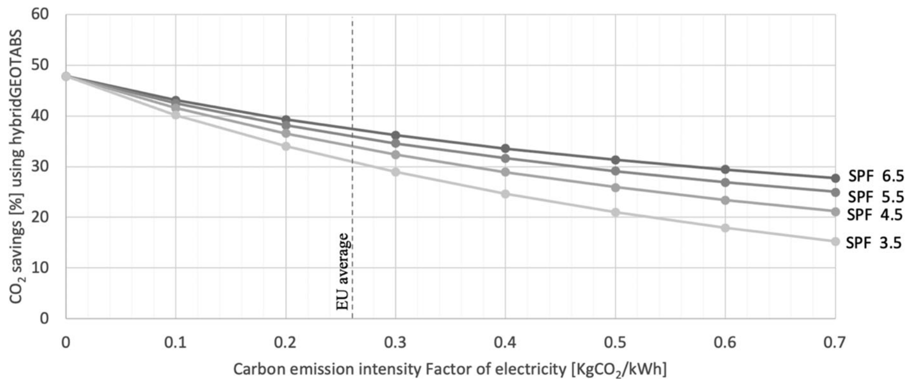

Fig. 12. Carbon emission savings from hybridGEOTABS under different SPFs of the GSHP in relation to carbon emission intensity factors.

lower shares of renewables in their electricity mix (e.g., high carbon intensity factor due to a high share of coal), hybridGEOTABS may result in lower savings than what is presented in this work. Figure 12 shows the savings from a hybridGEOTABS (y-axis) under varied GSHP SPFs compared to a non-GEOTABS gas-based system, with the carbon emission factor of electricity on the x-axis. These examples illustrate that the obtained CO_2 emissions savings are sensitive to the overall carbon emission intensity factors of the primary system GEOTABS and secondary system, which are constituted of the carbon intensities of the energy sources (e.g., electricity mix, natural gas) and conversion systems (e.g., SPF of the heat pump system, the efficiency of secondary system). This analysis confirms the findings from Boydens et al. (2021), that the future transition to higher shares of renewables in the electricity mix will have a significant impact on the implementation of hybridGEOTABS, allowing for further energy savings and lower environmental impact compared to a non-GEOTABS scenario.

Pre-simulated database for hybridGEOTABS building design at the early design stage

Building energy simulations are recommended to support designers in choosing the most efficient measures for their project at early design stages (Picco, Lollini, and Marengo 2014). However, at this early stage, choosing a conventional HVAC system based on rule of thumb calculations may be appealing in terms of cost because incorporating dynamic simulations early in the design increases engineering costs, especially for simulating complex HVAC systems. Offering estimated energy demands and environmental performance indicators of pre-simulated real cases from the building stock can help the designer make an informed choice on the feasibility of installing low-carbon HVAC solutions. Thus, the pre-simulated database can replace the need for detailed simulations at the early design stage, reducing engineering costs. The output of the presented work is used to feed in an integrated design, easy-to-use tool, as documented by Himpe et al. (2021). This easy-to-use tool can support designers in assessing the feasibility of using hybridGEOTABS in the early design stage by comparing their project to one of the database's pre-simulated cases. Such a tool can help designers better understand innovative low-carbon HVAC systems, resulting in a broader implementation of such systems in the building sector.

Conclusion and future work

This paper presented a methodology to assess the performance and the feasibility of implementing a hybrid and storage-integrated HVAC system (hybridGEOTABS) on a wide range of buildings. The method developed incorporated the different system component dynamics, building dynamics, TABS, and optimal controller). We developed a bottom-up modeling approach using parametric archetypes to transform real building data into BES models to estimate hourly heating and cooling loads. This approach was implemented on a wide range of non-residential buildings of 3 typologies (Offices, schools, and elderly homes). These non-residential typologies and their properties have been way less studied and documented in the literature compared to the residential building stock. Thus, in this work, we succeeded to create a comprehensive representation of the non-residential buildings in the EU comprising its diverse building typologies, and design parameters (geometry, internal heat gains, among others) under different climatic conditions (Warsaw, Brussels, and Madrid.

From analyzing the energy performance and CO_2 emissions of 94,000 cases, the hybridGEOTABS system showed high potential in reducing the primary energy and CO_2 emissions across the different variations in the EU non-residential buildings. hybridGEOTABS succeeded in reducing the median annual primary energy consumption by 52%, reaching 25 kWh/(m^2.a) for all typologies compared to a conventional heating and cooling system scenario. Following the same tendency by implementing hybridGEOTABS, the median CO_2 emissions are reduced to half reaching 5 $kgCO_2$/(m^2.a).

To further explore the magnitude of CO_2 reductions on the non-residential building stock. Given that the useful surface area modeled in this work corresponds to 280 Mm^2 of the non-residential building stock, by deploying hybridGEOTABS, CO_2 reductions of 1.2 million tons compared to the simulated non-GEOTABS scenario were achieved. Assuming hypothetically that hybridGEOTABS would replace today's installed conventional heating and cooling systems in 25% of the EU's non-residential stock (equal to 1595 Mm^2 ('BSO-Database: EU Building Stock Observatory' n.d) Savings of 6.4 million tons CO_2 emissions could be achieved. These findings highlight that hybridGEOTABS is a promising low-carbon technology that can play an important role in the decarbonization of the EU building sector.

Future work will address the extrapolation of the results presented in this work to the EU building stock level. Hence, accounting for the distributions of the energy-related properties discussed in this paper using weights for each EU member state. This further step will further investigate the future potential of the hybridGEOTABS in reducing the CO_2 emissions in the EU building stock as discussed by Mahmoud, Himpe et al. (2021c).

Nomenclature

BES = Building energy simulation
CGB = Condensed gas boiler
GSHP = Ground source heat pump
EC = Electric chiller
EEA = European Environment Agency
EER = Energy efficiency ratio
EPBD = Energy performance building
EU = European Union
GFA = Gross floor area
HVAC = Heating, ventilation, and air conditioning
MPC = Model predictive control
SPF = Seasonal performance factor
TABS = Thermally activated building systems
VEA = Flemish energy agency
VIPA = Flemish infrastructure fund for personal affairs

Greek letters

μ = Overall efficiency of a system

Acknowledgments

We would like to thank the Flemish Energy Agency (VEA) for providing us with data.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This research is part of the hybridGEOTABS project, which has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 723649 (MPC-GT).

ORCID

Rana Mahmoud http://orcid.org/0000-0003-3283-2429
Mohsen Sharifi http://orcid.org/0000-0002-6754-0568
Eline Himpe http://orcid.org/0000-0002-5109-0283
Jelle Laverge http://orcid.org/0000-0002-5334-1314

References

'BSO-Database: EU Building Stock Observatory' n.d. Accessed December 15, 2021. https://ec.europa.eu/energy/topics/energy-efficiency/energy-efficient-buildings/eu-bso_en.

The Non-Domestic National Energy Efficiency Data-Framework. 2020. (England and Wales) Geographical Annex'. 2021. Official Statistics. Department for Business, Energy & Industrial Strategy. https://www.gov.uk/government/collections/non-domestic-national-energy-efficiency-data-framework-nd-need.

Aditya, G. R., and G. A. Narsilio. 2020. Environmental assessment of hybrid ground source heat pump systems. *Geothermics* 87 (September):101868. doi:10.1016/j.geothermics.2020.101868

Alavy, M., H. V. Nguyen, W. H. Leong, and S. B. Dworkin. 2013. A methodology and computerized approach for optimizing hybrid ground source heat pump system design. *Renewable Energy* 57 (September):404–12. doi:10.1016/j.renene.2013.02.003

Allaerts, K., M. Coomans, and R. Salenbien. 2015. Hybrid ground-source heat pump system with active air source regeneration. *Energy Conversion and Management* 90 (January):230–7. doi:10.1016/j.enconman.2014.11.009

Arghand, T., S. Javed, A. Trüschel, and J.-O. Dalenbäck. 2021. A comparative study on borehole heat exchanger size for direct ground coupled cooling systems using active chilled beams and TABS. *Energy and Buildings* 240 (June):110874. doi:10.1016/j.enbuild.2021.110874

Babiak, J., B. W. Olesen, and D. Petras. 2007. *Low temperature heating and high temperature cooling: REHVA GUIDEBOOK No 7*. Brussels: REHVA.

Baetens, R., R. De Coninck, F. Jorissen, D. Picard, L. Helsen, and D. Saelens. 2015. OpenIDEAS - An open framework for integrated district energy simulations. In Proceedings of building simulation 2015. Hyderabad (India).

Bagdanavicius, A., and N. Jenkins. 2013. Power requirements of ground source heat pumps in a residential area. *Special Issue on Advances in Sustainable Biofuel Production and Use - XIX International Symposium on Alcohol Fuels - ISAF* 102 (February): 591–600. 10.1016/j.apenergy.2012.08.036.

Ballarini, I., S. P. Corgnati, and V. Corrado. 2014. Use of reference buildings to assess the energy saving potentials of the residential building stock: The experience of TABULA Project. *Energy Policy* 68 (May):273–84. doi:10.1016/j.enpol.2014.01.027

Bayer, P., D. Saner, S. Bolay, L. Rybach, and P. Blum. 2012. Greenhouse gas emission savings of ground source heat pump systems in Europe: A review. *Renewable and Sustainable Energy Reviews* 16 (2):1256–67. doi:10.1016/j.rser.2011.09.027

Boydens, W., D. Cóstola, A. Dentel, T. Dippel, L. Ferkl, A. Görtgens, L. Helsen, et al. 2013. *Improved system design and control of GEOTABS buildings: Design and operation of GEOTABS systems*. Finland: RHEVA, Guidebook No.20.

Boydens, W., L. Helsen, B. W. Olesen, L. Ferkl, and J. Laverge. 2021. *Renewable and storage-integrated systems to supply comfort in buildings: Pre-design and control for HybridGEOTABS projects*. Ghent (Belgium): A&S/books on Architecture and Arts. 10.5281/zenodo.5109932.

Bundesamt für Statistik. 2018. *Eidgenössisches Gebäude- Und Wohnungsregister- Federal register of buildings and dwellings*. Germany: Bundesamt für Statistik (BFS).

Catalina, T., J. Virgone, and V. Iordache. 2011. Study on the impact of the building form on the energy consumption. In Proceedings of building simulation 2011. Sydney: 12th Conference of International Building Performance Simulation Association.

Chua, K. J., S. K. Chou, and W. M. Yang. 2010. Advances in heat pump systems: A review. *Applied Energy* 87 (12):3611–24. doi: 10.1016/j.apenergy.2010.06.014

ComStock Analysis Tool. 2021. National renewable energy laboratory (NREL). https://www.nrel.gov/buildings/comstock.html.

Cupeiro Figueroa, I. 2021. *Short- and long-term optimal control of hybrid GEOTABS buildings*. https://lirias.kuleuven.be/retrieve/612480$$Dthesis_finalICF.pdf [freely available].

D'Agostino, D., B. Cuniberti, and P. Bertoldi. 2017. Energy consumption and efficiency technology measures in European non-residential buildings. *Energy and Buildings* 153:72–86. doi: 10.1016/j.enbuild.2017.07.062

Delghust, M. 2015. Improving the predictive power of simplified residential space heating demand models: A field data and model driven study'. PhD thesis., Ghent University.

Drgoňa, J., J. Arroyo, I. Cupeiro Figueroa, D. Blum, K. Arendt, D. Kim, E. P. Ollé, J. Oravec, M. Wetter, D. L. Vrabie, et al. 2020. All you need to know about model predictive control for buildings. *Annual Reviews in Control* 50 (January):190–232. doi: 10.1016/j.arcontrol.2020.09.001

Dymola. 2018. *Dymola for multi-domain modelling and simulation using modelica*. Claytex Services Limited. Accessed February 9, 2018. http://www.claytex.com/products/dymola/.

Economidou, M., B. Atanasiu, C. Despret, J. Maio, I. Nolte, O. Rapf, J. Laustsen, P. Ruyssevelt, D. Staniaszek, D. Strong, et al. 2011. *>Europe's buildings under the microscope*. Brussels: Buildings Performance Institute Europe (BPIE).

EEA. 2012. *Main climates of Europe - the European Environment Agency (EEA)*. European Environment Agency (EEA). https://www.eea.europa.eu/data-and-maps/figures/climate.

European Commission. 2020. The 2030 climate plan-stepping up Europe's 2030 climate ambition - investing in a climate-neutral future. 17 September 2020. Accessed December 1, 2020. https://eur-lex.europa.eu/.

Fisher, D. E., S. J. Rees, S. K. Padhmanabhan, and A. Murugappan. 2006. Implementation and validation of ground-source heat pump system models in an integrated building and system simulation environment. *HVAC&R Research* 12 (sup1):693–710. doi:10.1080/10789669.2006.10391201

G. Swan, L., and V. I. Ugursal. 2009. Modeling of end-use energy consumption in the residential sector: A review of modeling techniques. *Renewable and Sustainable Energy Reviews* 13 (8): 1819–35. doi:10.1016/j.rser.2008.09.033

Guo, Y., G. Zhang, J. Zhou, J. Wu, and W. Shen. 2012. A techno-economic comparison of a direct expansion ground-source and a secondary loop ground-coupled heat pump system for cooling in a residential building. *Applied Thermal Engineering* 35 (March): 29–39. doi:10.1016/j.applthermaleng.2011.09.032

Hamels, S. 2021. CO2 intensities and primary energy factors in the future European electricity system. *Energies* 14 (8):2165. doi:10.3390/en14082165

Himpe, E., M. Sharifi, R. Mahmoud, F. Jorissen, L. Helsen, W. Boydens, and J. Laverge. 2021. Development of the HybridGEOTABS design methodology for feasability study and pre-design. In Proceedings of Building Simulation 2021. Bruges.

Himpe, E., M. Vercautere, W. Boydens, L. Helsen, and J. Laverge. 2018. GEOTABS concept and design: State-of-the-art, challenges and solutions. In Proceedings of the REHVA Annual Meeting Conference Low Carbon Technologies in HVAC, 8. https://www.rehvam2018atic.eu/images/workshops/6/Himpe.pdf.

Holvoet, M. 2019. *Design study of public type buildings for the optimization of hot water systems, "Ontwerpstudie van Publieke Typegebouwen Voor de Optimalisatie van Warmwatersystemen*. Ghent (Belgium): Ghent University.

IEA. 2021. *Net zero by 2050: A roadmap for the global energy sector*. Paris: International Energy Agency (IEA). www.iea.org.

ISO 52000-1. 2017. *Energy performance of buildings-overarching EPB assessment-part 1: General framework and procedures (ISO 52000-1:2017)*. Brussels: International Organization for Standardization. Bureau for Standarisation.

Kohler, N., P. Steadman, and U. Hassler. 2009. Research on the building stock and its applications. *Building Research & Information* 37 (5–6):449–54. doi:10.1080/09613210903189384

Liu, Z., W. Xu, X. Zhai, C. Qian, and X. Chen. 2017. Feasibility and performance study of the hybrid ground-source heat pump system for one office building in chinese heating dominated areas. *Renewable Energy* 101 (February):1131–40. doi:10.1016/j.renene.2016.10.006

Mahmoud, R., J. Borrajo Bastero, E. Himpe, M. Delghust, and J. Laverge. 2019b. *A set of parametric geometries for the (sub)typologies studied. EU-H2020-hybridGEOTABS project Deliverable 2.2*. Ghent: Ghent University.

Mahmoud, R., E. Himpe, J. Borrajo Bastero, and J. Laverge. 2021b. *(D2.2_dataset02) internal heat gains and occupancy schedules in offices, schools and elderly homes*. Ghent: Ghent University. doi: 10.5281/zenodo.4769719

Mahmoud, R., E. Himpe, M. Sharifi, J. Borrajo Bastero, and J. Laverge. 2021a. *(D5.4_dataset01) HybridGEOTABS EU climate zones map*. Ghent: Ghent University. doi:10.5281/zenodo.4724629

Mahmoud, R., E. Himpe, M. Sharifi, J. Borrajo Bastero, and J. Laverge. 2021c. *Environmental impact assessment of hybridGEOTABS buildings. EU-H2020-hybridGEOTABS project Deliverable 5.4*. Ghent: Ghent University.

Mahmoud, R., M. Sharifi, E. Himpe, and J. Laverge. 2022. *(D2.1_dataset01) parameter values used in the optimal loads split algorithm to find the baseload*. Ghent: Ghent University. doi:10.5281/zenodo.5871509

Mahmoud, R., E. Himpe, M. Delghust, and J. Laverge. 2019a. A modelling approach to reduce the simulation time of building stock models. In Proceedings of Building Simulation 2019: 16th Conference of IBPSA, 16:1491–97. International Building Performance Association (IBPSA). doi:10.26868/25222708.2019.210860

Meierhans, R. A. 1996. Room air conditioning by means of overnight cooling of the concrete ceiling, November. https://www.osti.gov/biblio/392498.

Modelica. 2021. Modelica' – A Unified Object-Oriented Language for Systems Modeling Language Specification Version 3.5. Modelica Association Project (MAP). https://modelica.org.

Mustafa Omer, A. 2008. Ground-source heat pumps systems and applications. *Renewable and Sustainable Energy Reviews* 12 (2): 344–71. doi:10.1016/j.rser.2006.10.003

Neufert, E., and P. Neufert. 2000. *Neufert architects' data*. 3rd ed. Oxford, UK: Wiley-Blackwell.

Nguyen, H. V., Y. L. E. Law, M. Alavy, P. R. Walsh, W. H. Leong, and S. B. Dworkin. 2014. An analysis of the factors affecting hybrid ground-source heat pump installation potential in North

America. *Applied Energy* 125 (July):28–38. doi:10.1016/j.apenergy.2014.03.044

Olesen, B. W. 2012. Thermo active building systems using building mass to heat and cool. *ASHRAE Journal* 54 (2):44–52.

Park, S. H., W. J. Chung, M. S. Yeo, and K. W. Kim. 2014. Evaluation of the thermal performance of a thermally activated building system (TABS) according to the thermal load in a residential building. *Energy and Buildings* 73 (April):69–82. doi:10.1016/j.enbuild.2014.01.008

Peperkamp, H., and M. Vercammen. 2009. *Thermally activated concrete slabs and suspended ceilings*. DAGA 2009./DAGA 2009. Rotterdam, Netherlands.

Picard, D., and L. Helsen. 2018. Economic optimal HVAC design for hybrid GEOTABS buildings and CO2 emissions analysis. *Energies* 11 (2):314. doi:10.3390/en11020314

Picco, M., R. Lollini, and M. Marengo. 2014. Towards energy performance evaluation in early stage building design: A simplification methodology for commercial building models. *Energy and Buildings* 76 (June):497–505. doi:10.1016/j.enbuild.2014.03.016

ResStock Analysis Tool. 2017. National Renewable Energy Laboratory (NREL). https://www.nrel.gov/buildings/resstock.html.

Rhee, K.-N., and K. W. Kim. 2015. A 50 year review of basic and applied research in radiant heating and cooling systems for the built environment. *Building and Environment* 91 (September): 166–90. doi:10.1016/j.buildenv.2015.03.040

Sarbu, I., and C. Sebarchievici. 2014. General review of ground-source heat pump systems for heating and cooling of buildings. *Energy and Buildings* 70 (February):441–54. doi:10.1016/j.enbuild.2013.11.068

Scholenbouwen. 2019. Scholenbouwen Database. Accessed May 25, 2019. http://www.scholenbouwen.be/schoolvoorbeelden.

Self, S. J., B. V. Reddy, and M. A. Rosen. 2013. Geothermal heat pump systems: Status review and comparison with other heating options. *Applied Energy* 101 (January):341–8. doi:10.1016/j.apenergy.2012.01.048

Sharifi, M., I. Cupeiro Figueroa, R. Mahmoud, E. Himpe, L. Helsen, and J. Laverge. 2022b. Early-stage optimal design of hybrid GEOTABS buildings in terms of costs and CO2 emissions. *Energy Conversion and Management* 257:115392. doi:10.1016/j.enconman.2022.115392

Sharifi, M., R. Mahmoud, J. Borrajo Bastero, E. Himpe, and J. Laverge. 2021. *(D2.5) HybridGEOTABS key component sizing: methodology and guidelines*. Ghent: Ghent University. doi:10.5281/zenodo.4704647

Sharifi, M., R. Mahmoud, E. Himpe, and J. Laverge. 2019. Integrated sizing methodology for a HybridGEOTABS building. *ASHRAE Transactions* 125:222–30. https://www.techstreet.com/ashrae/standards/kc-19-c013-integrated-sizing-methodology-for-a-hybrid-geotabs-building?product_id=2080167.

Sharifi, M., R. Mahmoud, E. Himpe, and J. Laverge. 2022a. A heuristic algorithm for optimal load splitting in hybrid thermally activated building systems. *Journal of Building Engineering* 50: 104160. doi:10.1016/j.jobe.2022.104160

Spitler, J. D, and J. Cullin. 2008. Misconceptions regarding design of ground-source heat pump systems. In World renewable energy congress. Glasgow, Scotland.

VEA-EPB database. 2016. EPB database gathered till end 2016. Flemish Energy Agency. https://www.energiesparen.be/over_vea.

Verhelst, C. 2012. *Model predictive control of ground coupled heat pump systems in office buildings*. Belgium: KU Leuven.

VIPA. 2017. 'Erkenningsvoorwaarden Voor Nieuwe Woonzorgcentra En Centra Voor Kortverblijf of Nieuwe Delen van Bestaande Woonzorgcentra En Centra Voor Kortverblijf (Nieuwbouw En Verbouwing) – Toelichting'. Flemish Infrastructure Fund for Personal Affairs (VIPA). https://www.zorg-en-gezondheid.be.

Wilson, E. J., C. B. Christensen, S. G. Horowitz, J. J. Robertson, and J. B. Maguire. 2017. *Energy efficiency potential in the U.S. single-family housing stock* TP-5500-68670). Golde/TP-5500-68670). Golden, CO (United States): National Renewable Energy Lab. (NREL). doi:10.2172/1414819.

Wu, W., T. You, B. Wang, W. Shi, and X. Li. 2014. Evaluation of ground source absorption heat pumps combined with borehole free cooling. *Energy Conversion and Management* 79 (March): 334–43. doi:10.1016/j.enconman.2013.11.045

You, T., X. Li, W. Wu, W. Shi, B. Wang, and K. Soga. 2017. Coupled heating of ground-coupled heat pump system with heat compensation unit: Performance improvement and borehole reduction. *Energy Conversion and Management* 148 (September): 57–67. doi:10.1016/j.enconman.2017.04.050