# Interaction of GEOTABS and secondary heating and cooling systems in hybridGEOTABS buildings: towards a sizing methodology

*Mohsen* Sharifi[1*], *Rana* Mahmoud[1], *Eline* Himpe[1], and *Jelle* Laverge[1]

[1] Department of Architecture and Urban Planning, Building physics group, Sint-Pietersnieuwstraat 41-B4, B-9000, Ghent University, Belgium.

**Abstract**. GEOTABS, a combination of TABS with a geothermal heat pump, is a promising heating and cooling system for decreasing greenhouse gas emissions in the building sector. However, TABS has a time delay when transferring energy from the pipes to the room. So, when the heat demand changes fast, TABS cannot properly compensate the heat demand. In order to solve this problem and maintain thermal comfort in the room, the concept of hybridGEOTABS proposes using a fast secondary system to assist the TABS. Yet, there is no integrated method for sizing both systems in a hybridGEOTABS building, considering the interaction between the secondary system and GEOTABS. This study will provide an integrated sizing methodology for hybridGEOTABS buildings. To that purpose, in this paper the interaction between the secondary system and TABS is investigated for two different scenarios by using a preference factor between the TABS and the secondary system. The methodology starts from heat demand curves, an analytic model for TABS, and optimal control principles for TABS to minimize the total energy use while providing thermal comfort. Finally, the method is used for 4 case studies in different scenarios with different secondary systems. Preliminary results of this research indicate that the secondary system type doesn't have effect on the strategy of sizing. Therefore, designer can decide about secondary system type with investment and operating cost analysis.

## 1 INTRODUCTION

### 1.1 GEOTABS concept

Thermally activated building systems (TABS) create a good opportunity for substituting renewable resources for fossil fuels in buildings because they can work with low grade energy resources like geothermal energy. [1] In this regard, geothermal heat pumps become more important and easier to use. Consequently, the concept of GEOTABS as a combination of a geothermal heat pump and a thermally activated building system (TABS) as a package seems promising.

Additionally, geothermal heat pumps perform better when they provide a lower temperature for heating and a higher temperature of cooling. [2] Also, TABS can store energy in concrete and use it after peak load period. [3] Conclusively, GEOTABS can help in spreading the usage of geothermal heat pumps and will end in a more sustainable future.

Nevertheless, GEOTABS has some disadvantages. When fast changes appear in heat demand, GEOTABS cannot compensate heat demand properly. So, a secondary system is used to help the GEOTABS in fluctuations. Using a secondary system makes the design procedure complicated, since the interaction between TABS and secondary system might influence on the sizing and performance of system. This research aims at providing a straightforward method for designing TABS in early stage of design procedure considering the interaction between GEOTABS and secondary system. By that, some case studies can be investigated and the interaction of hybridGEOTABS will be disclosed.

### 1.2 Secondary system

High thermal mass and thermal inertia of TABS, which can be considered as advantages of TABS, can also be disadvantageous. When sudden and significant changes in heating or cooling demand appear, TABS needs to rapidly change its mode from heating to cooling and vice versa which is not easy for TABS due to its high thermal inertia. For solving this problem, a secondary system is used to help GEOTABS. Then, TABS and secondary system have specific shares in compensating heat demand. (Figure. 1) The baseload is the part of the heat demand that TABS provides and the rest is compensated by secondary system. In some situations TABS compensates heat demand completely, and in some cases partially. Consequently, the share of secondary system differs during the time and maximum difference between the heat demand curve and the baseload curve can be used to size the secondary system.

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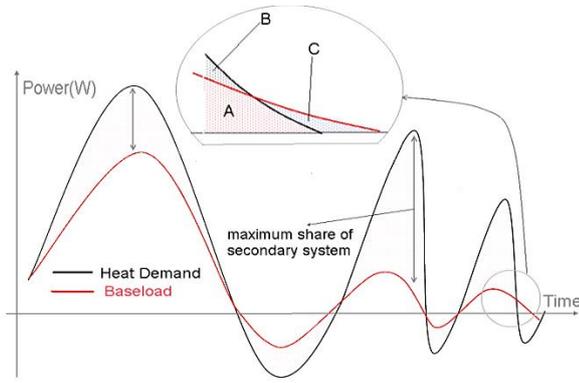[*] Corresponding author: mohsen.sharifi@ugent.be

**Fig. 1.** Share of TABS and secondary system from heat demand

Figure 1 represents an example of heating and cooling demand curve for a building (black curve), and a baseload curve (red curve). But for deriving the baseload, a detailed investigation on the performance of TABS in problematic moments is needed. (Figure 1, detail view) The idea of this research is to find the baseload for a hybridGEOTABS building and size both systems by comparing the baseload with heating and cooling demand curve. But, firstly we needed to provide a definition for the baseload, then based on the definition, a mathematical expression can be derived to calculate the baseload. Finally, the whole process is provided as a methodology for sizing the system and is tested for some case studies.

## 2 Methodology

### 2.1 Baseload

As a matter of fact, in hybridGEOTABS, the system has to decide between GEOTABS and the secondary system at every moment. Best combination of power of GEOTABS and secondary system for a year can lead us to the best sizing strategy. And this combination is obtainable via the baseload concept. (Figure 1) After looking at the performance of TABS and its limitations, it is possible to find a general definition for the baseload. As mentioned, if fast changes are happening and TABS is supposed to compensate them, in some moments the power of TABS will be higher than the heat demand. (Figure 1, detail view) Then, if a secondary system is used, wasting energy will happen because the secondary system has to cool the room which has been warmed by the TABS. (Figure 2, region C) Therefore, to avoid wasting energy, the future of the system must be considered when the system is deciding between the TABS and secondary system. However, sometimes it is better to waste some energy (increasing C region) in the future but increase the share of TABS at the moment (increasing A and decreasing B), for example if the secondary system is less energy efficient than the GEOTABS.
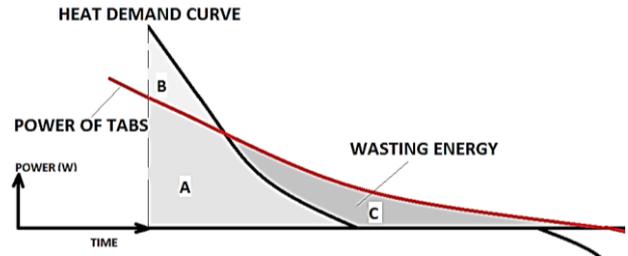


**Fig. 2.** An example of problematic moments in hybridGEOTABS. "A" is heat from surface of TABS, "B" is the heat of secondary system, and "C" is heat from TABS and secondary system in opposite sides at the same time, and thus called wasted energy

In other words, we need an optimal control of the system for minimizing the total energy use. To sum up, the "baseload" is the maximum power that the TABS can provide without resulting in energy wasting in the near future.

All these explanations can be presented by an optimization for total energy use of system for a long period of time. (Equation 1)

$$\sum_1^n E_{tot} = \sum_1^n ( \; P_{SS} + \dot{Q}_{heatPump} \; / PF) \quad (1)$$

Where $E_{tot}$ is total energy use divided by time step.
$P_{SS}$ is the power of the secondary system in every time step;
$\dot{Q}_{heatPump}$ is the power from TABS in every time step;
PF is the preference factor (discussed in section 3.2 ).
Optimizing equation 1 has a limitation which is thermal comfort range (power demand of the building) which completes the baseload function. (Figure 3)
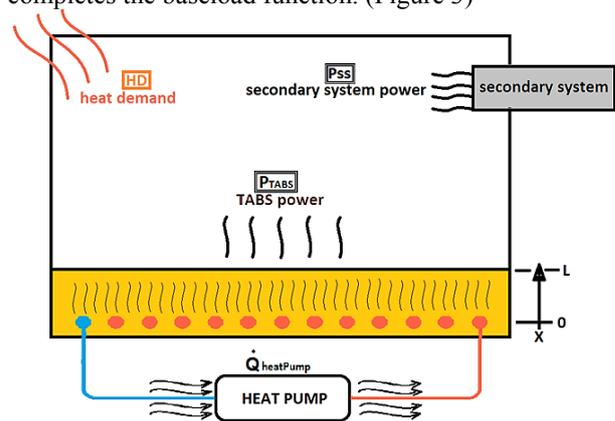


**Fug. 3.** Energy balance in a building, schematic interaction between heat demand, secondary system, and GEOTABS.

### 2.2 Baseload function

To find a mathematical expression of the interaction between building, secondary system and GEOTABS, the energy balance is considered. (Figure. 3) The energy balance in the thermal zone can be shown as equation 2.

$$HD = P_{SS} + P_{TABS} \quad (2)$$

Where HD is the heat demand of the building per time step ($\dot{Q}$) . PSS is the power from the secondary system

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* Corresponding author: mohsen.sharifi@ugent.be

and $P_{TABS}$ is the power of TABS. For finding the baseload, the share of both systems must be found with the considerations mentioned in the definition of the baseload.

The mathematical expression of the baseload must represent equation 1 while considering equation 2. So, the baseload can be found by an optimization for minimizing equation 1, which is an optimal control for having minimum energy use. In this optimization, $\dot{Q}_{heatPump}$ is optimizing parameter and is optimized for every time step for a year and as the time step is one hour, 8760 parameters are optimized.

Also, $P_{SS}$ is found from equation 2 for every time step. Yet, the problem is that $\dot{Q}_{heatPump}$ in equation 1 is not $P_{SS}$ in equation 2. (Figure 3) So, we need a model to show the relation between power from heat pump which goes to the pipes ($\dot{Q}_{heatPump}$) and power of TABS which is released to the room. A glance at transient heat transfer in a concrete slab reveals that the relation between $P_{TABS}$ and $\dot{Q}_{heatPump}$ can be extracted from the transient heat transfer equation of TABS. [2][4] Since we just needed the power of TABS on the surface, the equation is presented as:

$$P_{TABS}(t) = \dot{q}_{max} + (\dot{q}_0 - \dot{q}_{max}) \cdot \exp(-\beta^2 Fo) \quad (3)$$

Where $P_{TABS}$ is specific power of TABS (w/m2), $Fo = t. \alpha_C / L^2_C$, $L_C$ is the concrete thickness and $\alpha_C$ the thermal diffusivity of concrete. $\dot{q}_{max}$ is the specific power of heat pump (w/m2).

and, $\beta$ is a learning factor for the prediction error correction. Depending on the needed accuracy the order of $\beta$ can be different. In this research and for developing the methodology the first order of $\beta$ is used in the calculations. This equation can also represent the first order resistance-capacitance model of the TABS. [5] With equations 1, and 3 the optimization algorithm is complete. Equation 2 is the objective function, equation 3 and maximizing the power of GEOTABS are the constraints. After defining the objective function and extracting constraints, an optimization algorithm was used. The optimization parameter is $\dot{q}_{heatPump}$ for every time step. Since the time step is one hour, 8760 parameters are optimized. For every time step of the system $\dot{q}_{heatPump}$ is first considered as baseline. Then, $\dot{q}_{heatPump}$ is changed and if the influence of this change is acceptable, the direction of the change is kept the same. If the influence of the change on the system is not accepted, the direction of the change is reversed. This will be continued for 500 iterations.

By repeating this iteration for every time step chronologically, the best point is found for every time step. Conclusively, the output will be an optimized baseload curve. The size of the secondary system can be found by comparing the baseload and the heat demand curve.

## 3 Case study

### 3.1 Heat demand curves

The methodology is now applied to 4 cases. In order to do this, heating and cooling demand curves were calculated for each case study and a Matlab code was written for optimization process. The four case-study buildings have the same location and climate (Belgium), typology (office building), and thermal comfort temperature range (heating demand for less than 20∘C and cooling demand for more than 26∘C indoor operating temperature). (Please refer to [6] for details). Table 1 lists the characteristics that are different between the four cases. Furthermore, the TABS characteristics are the same for all cases. (Table 2) The distance between pipes, concrete thickness, thermal conductivity and mass of concrete, and etc. are considered as usual and typical values. [2,7,8]

**Table 2.** Parameters of TABS in all case studies

| parameter | value |
|---|---|
| Thermal conductivity λc (W/mK) | 1.4 |
| Concrete thickness Lc (mm) | 100 |
| Pipes distance D(mm) | 150 |
| Density of concrete ρ(kg/m3) | 840 |
| thermal capacitance C(J/kg) | 2100 |
| Pipes diameter d(mm) | 20 |

For the TABS however, on one hand, the characteristics can be different in different cases, but on the other hand, they can be roughly assumed the same in all cases in predesign stage. Briefly, characteristics of TABS are not the issue in the predesign stage. In this research TABS is designed to deliver heat mainly via the ceiling and the

**Table 1.** different parameters in different cases studies

| Case number | Glazing (%) | Volume (m³) | Area (m²) | Heat loss area (m²) | Number of floors | U-value envelope (W/m². k) | U-value windows (W/m². k) | Internal gains* | Orientation |
|---|---|---|---|---|---|---|---|---|---|
| Case 1 | 15% | 26579 | 7010 | 6749 | 6 | 0.24 | 1,5 | Low | South |
| Case 2 | 15% | 8623 | 2543 | 2893 | 4 | 0.15 | 1 | High | West |
| Case 3 | 40% | 25446 | 6470 | 6773 | 5 | 0.24 | 1,5 | High | West |
| Case 4 | 3% | 25875 | 4402 | 6877 | 3 | 0.24 | 1,5 | High | West |

* Corresponding author: mohsen.sharifi@ugent.be

whole ceiling area is covered by TABS, since optimization in the area of TABS is not considered as a big issue in this case. [7]

### 3.2 Preference Factor

Regarding the complexity of hybridGEOTABS, sizing secondary systems seems quite difficult. The difference between the performances of GEOTABS and the secondary system is the main reason for this complexity. Considering these facts, this paper aims at investigating the interaction between GEOTABS and the secondary system.

To have the exact amount of energy use, the overall efficiency of the secondary system and of the GEOTABS must be calculated exactly, considering as well distribution losses etc. In this research, these efficiencies are not calculated in detail, but a preference factor is used to approximate the relation between the overall efficiencies of both systems because in this research energy use optimization is not the target. PF is considered as the ratio of the coefficient of performance (COP) of GEOTABS to COP of the secondary system which represents the ratio of overall primary energy efficiency of both systems.

Conclusively, results for different PF having GEOTABS as primary system, can show the influence of secondary system performance on total system because when we change the preference factor, in fact we are changing the secondary system type.

To calculate the PF, a ground source heat pump coupled with concrete core activation is considered as the primary system (GEOTABS). The COP of GEOTABS is considered as 5.5 in heating and 6.5 in cooling mode. [8] For the secondary system, two different scenarios are considered:

1. A gas Condensing boiler with 90% efficiency and radiators with 90% efficiency. For cooling, a Chiller is considered with energy efficiency ratio (EER) 3 and an air handling unit with the efficiency of 0.97.

Gas to electricity primary energy conversion factor is assumed 2.5. So in this scenario, PF in heating mode is 2.5 and in cooling mode it is 2.

2. In this optimistic scenario, PF is assumed 4 in heating and 5 in cooling mode. If free cooling is used with COP of 12, PF of 5 might be possible in cooling. [8] However, these assumptions might be even impossible in reality, they are useful for investigating the effect of the secondary system type on sizing strategy.

## 4 Results and discussion

### 4.1 Results

Among all the available output data, maximum heat demands, maximum share of the secondary system, and the critical conditions in which the secondary system is used, are considered as important and decisive outputs. (Table 3)

Looking at the share of secondary system for almost a year (350 days), we tried to provide a strategy of sizing the secondary system based on peak demand day for secondary system. (Figures 4 and 5) In this regard, the comparison between the peak demand days in different scenarios and different cases is important.

**Table 3** Total energy use for GEOTABS in two different scenarios, time step when maximum demand for secondary system happens can show the effect of the secondary system type on the performance of system

| Case number | GEOTABS total annual energy use in heating mode (KWh/m²) | | GEOTABS total annual energy use cooling mode (KWh/m²) | | Time of the year for maximum heating for secondary system (hour) starting from January 10th | | Time of the year for maximum cooling for secondary system (hour) starting from January 10th | |
|---|---|---|---|---|---|---|---|---|
| | Scenario 1 | Scenario 2 | Scenario 1 | Scenario 2 | Scenario 1 | Scenario 2 | Scenario 1 | Scenario 2 |
| **1** | 9.20 | 11.93 | 0.33 | 1.00 | 8117 | 8117 | 5344 | 5344 |
| **2** | 16.79 | 17.24 | 0.30 | 1.96 | 701 | 701 | 5344 | 5344 |
| **3** | 16.62 | 20.86 | 0.56 | 10.85 | 1230 | 1230 | 5047 | 5047 |
| **4** | 17.48 | 21.77 | 0.11 | 0.14 | 479 | 1743 | 5344 | 5344 |

* Corresponding author: mohsen.sharifi@ugent.be

**Table 4.** Heat demand and secondary system size different case studies in 2 scenarios

| Case number | Maximum heating demand (KW) | Maximum cooling demand (KW) | Maximum power of secondary system in heating (KW) | | Maximum power of secondary system in cooling (KW) | | Size of secondary system as a percentage of maximum heat demand (%) | | Size of secondary system as a percentage of maximum cooling demand (%) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Scenario 1 | Scenario 2 | Scenario 1 | Scenario 2 | Scenario 1 | Scenario 2 | Scenario 1 | Scenario 2 |
| 1 | 76.47 | -107.18 | 76.4 | 70 | -106.7 | -104.3 | 100 | 100 | 100 | 92 |
| 2 | 17.69 | -49.93 | 15.3 | 14 | -49.8 | -48.7 | 86 | 79 | 100 | 98 |
| 3 | 125.39 | -258.45 | 78.8 | 105 | -248 | -211 | 63 | 84 | 96 | 82 |
| 4 | 66.99 | -72.29 | 36.2 | 30 | -72.2 | -72.2 | 54 | 45 | 100 | 100 |
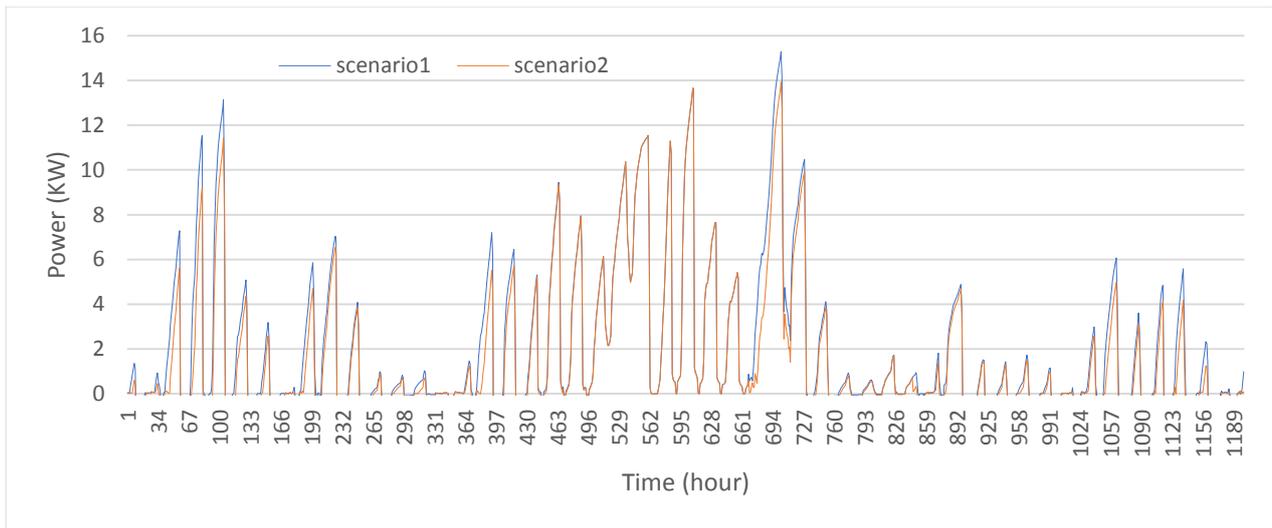


**Figure 4.** Share of the secondary system in case number 2 for both scenarios for 50 days starting from January 10th
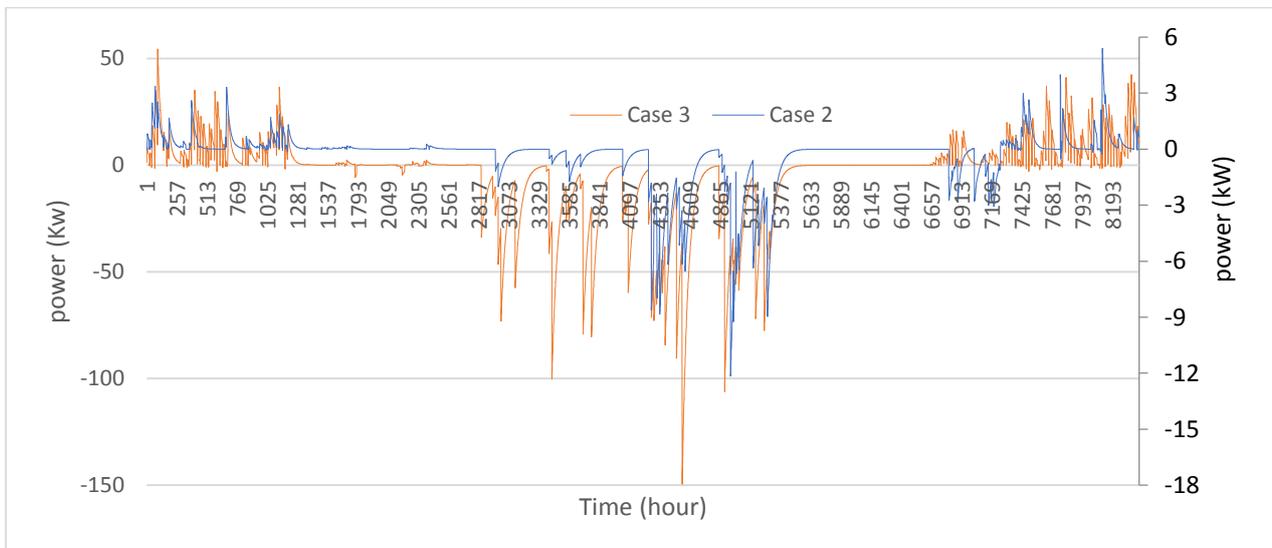


**Fig. 5.** Difference between share of the secondary system in 2 scenarios for cases number 2 and 3 for a year starting from January 10th, in both cases the difference in midseason is less than winter and summer. For a better comparison Case 2 vertical axis is in right side and horizontal axes are in different levels.

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\* Corresponding author: mohsen.sharifi@ugent.be

## 4.2 Discussion

The influence of the secondary system type on the performance of the system is discussed based on tables 3 and 4. Table 3 shows investigation on sizing of the secondary system for two scenarios in different cases. Table 4 shows the performances for 2 scenarios in terms of annual energy use. Any meaningful relation between the size of the secondary system and scenarios cannot be seen. However, total energy use has relationship with type of the secondary system. In table 4, we can see that the total energy use for GEOTABS in scenario number 2 is always higher than scenario number 1.

In case number 1, size of the secondary system in cooling and heating mode is the same in two scenarios.

In case number 2, size of the secondary system in heating and cooling mode in scenario 1 is smaller than scenario 2.

In case number 3, size of the secondary system in heating mode in scenario 1 is smaller than scenario 2, while in cooling mode the size of the secondary system in scenario 1 is bigger than scenario 2.

In case number 4, size of the secondary system in cooling mode is the same in two scenarios and in heating mode size of the secondary system in scenario 1 is

All previous statements show that finding a meaningful relation between type and size of the secondary system in hybridGEOTABS is not feasible. However, the strategy of sizing can be the same in all cases and scenarios. So, looking at the conditions in which maximum demand for the secondary system happens is useful.

Table 4 shows that Maximum cooling demand for the secondary system always happens in the same time step - every time step is 1 hour- in both scenarios. Furthermore, in 3 cases the time step is the same -5344 when it is in day time in the middle of July- most probably because all cases are in the same location with the same typology. Conclusively, holding the same strategy for sizing the size of the secondary system, designer can decide about the type of the system after predesign stage with cost benefit analysis. Also, the strategy of peak demand day for cooling is accessible.

Nevertheless, such time step cannot be seen in heating mode. Maximum heating demand for the secondary system happens in different time steps in different cases. However, for both scenarios maximum demand happens in the same time step. By that, the effect of type of the secondary system on the sizing strategy for heating is also rejected. But, the strategy of peak demand day for heating is not applicable so far and more case studies must be investigated. However, in case number 4 which is a very special case with only 3 percent of glazing area, the time step for maximum heating demand for the secondary system is not the same in both scenarios.

Figures 4 and 5 can show the behaviour of the demand for secondary system. However, the demand for GEOTABS can be higher in scenario 2, the peak demand for secondary system is not a function of PF and type of the secondary system. Even local maximum and minimum demands for the secondary system happens in the same time steps of two scenarios.(Figure 4) In other words, there are some moments when TABS must not be used and such moments are critical for sizing the secondary system. (Figure 5) In this kind of moments, using TABS must not be used even if the PF is 4 or 5. In these moments, share of secondary system in two different scenarios are almost the same because it is nearly zero. However, in winter and summer when there is peak demand, there is difference between shares of secondary system in two scenarios. In these particular moments, the share the secondary system is lower in scenario 2 than scenario 1. (Figure 5) To sum up, despite the fact that the higher the PF, the more moments for TABS and the less moments for the secondary system, the maximum demand for the secondary system is not changed by changing PF. However, this conclusion is preliminary, as it is related to only few case-studies and load shifting effect is not considered in the methodology yet. A more conservative conclusion is, the strategy for sizing the secondary system is not a function of PF and the secondary system type. So, in the next steps of research, considering PF as an effective parameter for designing the system , we are going to provide some general rules for designing hybridGEOTABS.

## 4.3 Perspectives

This research is ongoing and in next steps more case studies will be investigated. By that, a general guideline for sizing components of system, regardless of type of secondary system, will be presented. In this research, preheating and precooling effect of TABS is not considered. This effect will be included in the methodology and the baseload in next steps.

Peak shaving and decreasing maximum heat demand are considered as important advantages of TABS. [3,9,10] These advantages can be exploited by taking into account preheating and precooling effect in the baseload algorithm.

For understanding these advantages of TABS in changing heat demand curve and peak shaving, the definitions of thermal mass and thermal constant must be considered. [8] The indoor operating temperature has a delay in responding to heat gains and losses. This potential helps heating and cooling system to adapt itself to have a better performance in providing thermal comfort. Also, 20∘C and 26∘C indoor operating temperatures, generally accepted as thermal comfort margin, can help the heating and cooling system to work

more efficiently. Heating and cooling system can decrease the indoor temperature till 20°C in cooling mode without hurting thermal comfort. But normally, it doesn't happen because it will increase energy use in conventional heating and cooling systems. But in the case of TABS, it even decreases the energy use since part of this energy comes from the building itself since energy can be stored in the TABS and concrete. This effect can be used for peak shaving, too. [11]

By that, many severe slopes and peaks in heat demand curve are smoothed and the periods when TABS can provide thermal comfort will be increased. It also decreases the peak demand which decreases size of GEOTABS and the secondary system.

## 5 Conclusion

Understanding the influence of the secondary system type in the sizing procedure, especially in predesign stage, is crucial for designing hybridGEOTABS systems. Hence, in this research, hybridGEOTABS with a focus on secondary system was investigated. Therefore, two scenarios were considered for finding the influence of different types of secondary system in sizing procedure. An integrated methodology was developed for sizing secondary system in different scenarios. The methodology was used for 4 case studies to investigate the application of the methodology. Preliminary results indicated that no matter what type of secondary system is going to be used, strategy for sizing doesn't change in predesign stage. However, size of the secondary system can be altered with post processing. So, considering operating and investment costs, designer can decide about secondary system.

A strategy for sizing the secondary system was discussed implicitly. Such strategy can be discussed in detail with more proves only with investigating more case studies.

## Acknowledgment

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* Corresponding author: mohsen.sharifi@ugent.be