# Understanding Optimization Factors in Sizing Ground-Source Heat Pumps in Hybrid Systems

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**Abstract**

Ground-source heat pump (GSHP) systems are clean, renewable alternatives to conventional space heating and cooling. Hybrid GSHPs, in which a ground loop meets base load and a conventional system meets peak load are an economical alternative to costly installations. A recent methodology developed at Ryerson University in sizing hybrid GSHP systems has shown great success compared to current rules-of-thumbs used by the industry. Using this mathematical, computational approach, a sensitivity analysis was performed to determine the effects of geographical location (weather patterns) and operating costs on sizing hybrid GSHP systems.

**Keywords**: Ground Source Heat Pumps; Geothermal; Economics; Methodology; Sensitivity Analysis

**Résumé**

Les thermopompes utilisant le sol comme source de chaleur (GSHP) constituent des solutions de remplacement propres et renouvelables aux installations classiques de chauffage et declimatisation des locaux. Les installations à GSHP hybrides, qui combinent une boucle souterraine fournissant une puissance de base avec des appareils classiques assurant les charges de pointe, représentent une solution avantageuse et économique. Une méthodologie de dimensionnement des installations à GSHP hybrides récemment élaborée à l'Université Ryerson a produit d'excellents résultats en comparaison des règles pratiques actuellement utilisées par l'industrie. Au moyen de cette méthode mathématique et numérique, une analyse de sensibilité a été effectuée pour déterminer les effets de l'emplacement géographique (situations météorologiques) et des coûts d'exploitation sur le dimensionnement des installations à GSHP hybrides.

**Mots clés** : thermopompes utilisant le sol comme source de chaleur, géothermie, économie, méthodologie, analyse de sensibilité

## 1. Introduction

Space heating and cooling is responsible for a large portion of a building's total energy demands. Due to increasing environmental concerns and potential resource shortages, there is an ongoing drive to develop and implement sustainable alternatives. Ground-source heat pump (GSHP) systems have shown great success and potential, making them a popular clean renewable alternative to consider [1]. However, high upfront costs and long payback periods are currently presenting obstacles to significant market penetration.

In many cases, market penetration impedance for GSHP systems can be alleviated with the use of appropriate computational tools for design analyses. Improving the economic outlook of potential installations can be addressed by hybridizing GSHP systems with an auxiliary system; the buildings' base load energy demands are met by the GSHP and any excessive peaks are met by an auxiliary system. Due to the nature of sizing GSHP systems, general rules-of-thumb currently used by the industry do not always correspond to an optimized design [2].

Current analyses to determine the GSHP capacity within a hybrid system are case specific and time consuming. Determining the required ground loop length involves a tedious process and the use of several software packages, which do not consider hybrid systems. This barrier prevents GSHP installers from determining an optimal design. A rigorous mathematical, computational approach to determine the GSHP capacity within a hybrid system has been developed by Alavy et al. [3]. The methodology shows that rough rules-of-thumb currently used by the industry do not always correspond to an optimized design. Since this methodology was developed recently, sensitivity analyses remain important to explore. By using this methodology, an investigation can be carried out to determine the effects of geographical location (weather patterns and utility costs) and operating costs on sizing hybrid GSHP systems.

## 2. Sensitivity analyses: parameters used

The ten real buildings analyzed in this paper are detailed in Table 1 ranging from large residential to commercial. Tables 2 and 3 contain parameters that will be used for the analyses; the criteria in determining the optimal GSHP size is based on one which produces the minimum total costs in net present value (NPV). Inflation and interest rates were taken into consideration in determining the annual savings and payback periods (PBPs). An operating duration of 20 years was selected on the notion that payback-periods (PBPs) exceeding this would be an unappealing investment. In addition, many boilers, cooling towers and heat pumps can operate for a 20 year lifespan [1]. For a better understanding of the methodology used and how the optimal GSHP size is determined, it is recommended to refer to [3].

Table 1: Building Information (data courtesy of CleanEnergy™)

| Building Information | Sector |
|---|---|
| 1. Hospital (Hosp.) | Commercial |
| 2. Office | Commercial |
| 3. Restaurant (Rest.) | Commercial |
| 4. Fast-Food Restaurant (FF Rest.) | Commercial |
| 5. Transit Facility (TF) | Commercial |
| 6. Mid-rise, Multi-residential (MR) | Residential |
| 7. High-rise, Multi-residential A (HR A) | Residential |
| 8. High-rise, Multi-residential B (HR B) | Residential |
| 9. High-rise, Multi-residential C (HR C) | Residential |
| 10. School | Commercial |

Table 2: General Costs of Hybrid GSHP Components (data courtesy of CleanEnergy™)

| Item | Cost |
|---|---|
| Ground heat exchanger (installation and materials) | $65.6/meter |
| Cooling tower, plate heat exchanger including controls and auxiliary equipment | $12/kW of tower design capacity |
| Boiler (efficiency = 78%) | $20/kW of boiler design capacity |

Table 3: General Design Parameters (data courtesy of CleanEnergy™)

| Parameters | Value |
|---|---|
| Cooling Design Entering Water Temperature to Heat pump | 29.4°C |
| Heating Design Entering Water Temperature to Heat pump | 1.7°C |
| Heat Pump | CleanEnergy Developments/ PC0018 (COP=3.1, EER=12.9) |
| Soil Thermal Conductivity | 2.94 W/m·K |
| Soil Thermal Diffusivity | 0.072 $m^2$/day |
| Duration of Operation | 20 years |
| Borehole Thermal Resistance | 0.136 m·K/W |
| Pipe Resistance | 0.06 m·K/W |
| Pipe Size | 32 mm |
| Borehole Diameter | 127 mm |
| Grout Thermal Conductivity | 1.47 W/m·K |
| Number of boreholes across | 11 |
| Number of boreholes down | 4 |
| Inflation Rate | 4% |
| Interest Rate | 8% |

*COP (coefficient of performance); EER (energy efficiency ratio)*

## 3. Test #1 - electricity rates: fixed vs. time of use

Conventional heating and cooling consumes large amounts of natural gas and electricity, with operating costs affected by rising costs of resources. This analysis will determine the effects of fixed vs. time of use (TOU) electricity rates. The most recent weather data, the CTMY2 (Canadian typical meteorological year) was used to simulate the buildings' hourly loads using eQUEST Version 3.64 [4] and [5].

Table 4 presents the operating costs and conditions for this analysis. Based on costs calculator provided by Ontario Energy Board [6], an averaged electricity taxes and fees rate was determined (~95%). I.e., $1/kWh electricity rate results in a tax-inclusive cost of $1.95/kWh. As a result, after adjustments, the electricity prices used in this analysis are presented in Table 5.

Table 4: Toronto Operating Costs and Conditions

| | |
|---|---|
| Operating Duration | 20 years† |
| Ground Temperature | 10°C† |
| Natural Gas | $0.35/m3† |
| Electricity Fixed Rate | $0.1/kWh† |
| 2012 Commercial & Residential TOU Rates<br>Peak<br>Mid-Peak<br>Off-Peak | <br>$0.117/kWh[7]<br>$0.1/kWh[7]<br>$0.065/kWh[7] |

*†Data courtesy of CleanEnergy™*

Table 5: Adjusted Toronto Electricity Costs

| | |
|---|---|
| Electricity Fixed Rate | $0.17/kWh |
| 2012 Commercial & Residential TOU Rates<br>Peak<br>Mid-Peak<br>Off-Peak | <br>$0.228/kWh<br>$0.195/kWh<br>$0.127/kWh |

For demonstrative purposes, building #6 (Table 1), a mid-rise multi-residential building will be discussed. Applying the fixed electricity rate of $0.17/kWh resulted in an optimal system size with a shave factor (SF) of 0.37 (the GSHP meets 37% of peak demand with the balance met by a conventional system). As mentioned in [3], the optimal SF is compared to SF values that correspond to 0 and 0.7 for residential buildings, which denote a purely conventional system (no GSHP) and 70% of the building's peak energy demand by the GSHP, respectively.

The results are illustrated in Table 6. It is apparent that the conventional system prevailed in achieving minimum upfront costs ($81,694). However, the optimal hybrid GSHP system proved to be the most cost effective over the long run for 20 years of operation; meeting 77.7% of the building's total energy needs.

Table 6: Mid-Rise Multi-Residential Building (Cooling Dominant)

| **SF** | **Ground-loop Length (m)** | **TEDM (%)** | **Total Costs NPV ($)** | **IC ($)** | **AOPC ($)** | **PBP (years)** |
|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 975,414 | 81,694 | 44,686 | - |
| 0.37* | 3,743 | 77.7% | 868,766 | 279,598 | 29,458 | 13 |
| 0.7 (Standard) | 6,130 | 98.4% | 917,800 | 418,400 | 24,970 | 17 |

*TEDM (total energy demands met); IC (initial costs); AOPC (annual operating costs)*
**Optimal system size*

$$\text{Total Savings} = (\text{Total Costs NPV})_{\text{Standard}} - (\text{Total Costs NPV})_{\text{Optimal Design}} \quad (1)$$
$$\text{IC Savings} = (\text{IC})_{\text{Standard}} - (\text{IC})_{\text{Optimal Design}}; \quad (2)$$

Applying equations (1) and (2), the optimal design for the mid-rise multi-residential building provided significant savings, with IC savings of $138,800, a total savings of $49,000 and PBP reduced by four years. It is evident that if an optimal SF exists it will outperform a purely conventional system. Hence, the remaining analyses will focus on comparing the net changes between the optimal-design determined by the methodology to that of the rule-of-thumb SFs currently used in the industry (0.7 for residential, 1 for non-residential). A positive value, in equations (1) and (2) denotes net savings by the optimal design compared to standard sizing.

The results are illustrated in Figure 1 and Table 7. GSHP installations for Buildings #1 and #2 were uneconomical and excluded from the figure. The low rates of natural gas make it uneconomical to install GSHPs for buildings #1 and #2, the hospital and office, because they are extremely heating dominant. Although the standard SF for sizing GSHPs for residential buildings is 0.7, the SFs for buildings #6-9 did not exceed 0.42. Substantial savings can be achieved using the optimal design which produces a minimum TEDM of 71% by HR A (building #7). The same patterns are observed for non-residential buildings. The SFs are well below 0.7 (70%) and the minimum TEDM is 83%. It is established that if the PBP is greater than the duration of operation (20 years), the system is uneconomical. For buildings #5, #7, #8 and #10 using the standard SFs resulted in long PBPs. According to Table 7, if an optimal SF exists, its PBP will be shorter than the standard PBP.

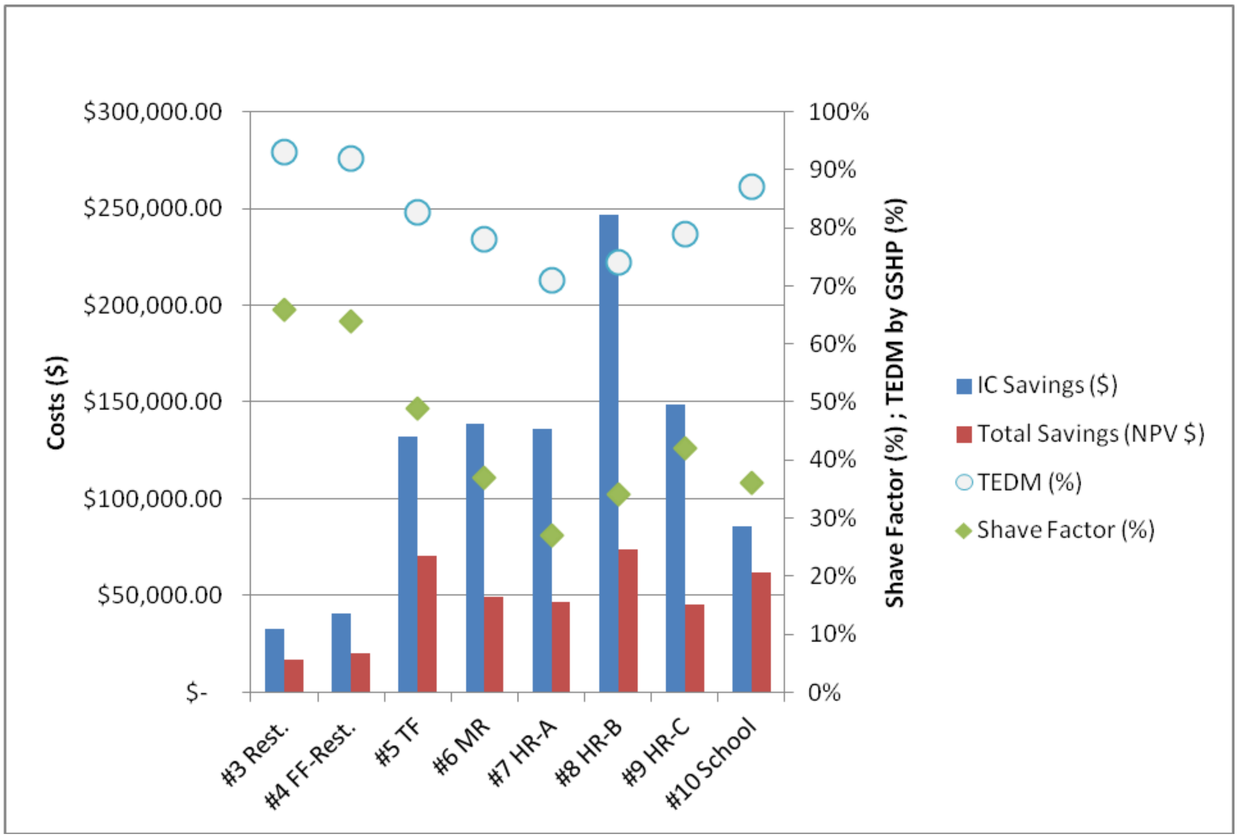


Figure 1: Toronto Fixed Electricity Rates Results

Table 7: Payback Periods – Toronto Fixed Electricity Rates

| PBP (Years) | Building | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | #3 Rest. | #4 FF-Rest | #5 TF | #6 MR | #7 HR-A | #8 HR-B | #9 HR-C | #10 School |
| Optimal PBP | 12.5 | 12.8 | 14.4 | 13 | 12.7 | 13.5 | 12.7 | 15.8 |
| Standard PBP | 14.5 | 15 | 20 | 17 | 18.7 | 18.1 | 15.9 | 30 |

The net difference (fixed vs. TOU rates) are calculated as follows:

$\Delta$Total Savings = (Total Savings)$_{TOU}$ – (Total Savings)$_{Fixed}$ (3)
$\Delta$IC Savings = (IC Savings)$_{TOU}$ – (IC Savings)$_{Fixed}$ (4)
$\Delta$PBP = (PBP$_{Optimal\ Design}$)$_{Fixed}$ – (PBP$_{Optimal\ Design}$)$_{TOU}$ (5)
$\Delta SF_{Optimal\ Design}$ = $(SF_{Optimal\ Design})_{TOU}$ - $(SF_{Optimal\ Design})_{Fixed}$ (6)

**Note: SF = Shave Factor*

Based on equations 3 to 6, TOU rates are more economical than fixed rates if values for $\Delta$Total Savings, $\Delta$IC Savings or $\Delta$PBP are positive. For the case of $\Delta$SF (net SF), a positive value indicates the TOU's system size is larger than the fixed rates' and smaller if it were negative.

The results for this analysis are presented in Figure 2. The restaurants showed reduced costs due to long operating hours and high cooling demands during cheaper off-peak rate times. This contributed to downsizing of the GSHP system for these buildings; reducing the upfront costs contributed to a positive $\Delta$Total Savings and $\Delta$IC Savings. However, this reduction resulted in a decrease in annual operating costs savings which contributed to longer PBPs (Table 8).

For the case of the school (building 10), most of the cooling demands occur during peak rates. As a result, the ground-loop length was increased ($\Delta$SF=0.03) when TOU rates were considered resulting in a negative $\Delta$Total Savings and $\Delta$IC Savings. The hospital's and office's heating dominance prevents feasibility for a GSHP system as in the electricity fixed-rate scenario. As observed, comparing between fixed and TOU rates, an increase in SF results in poorer economics.

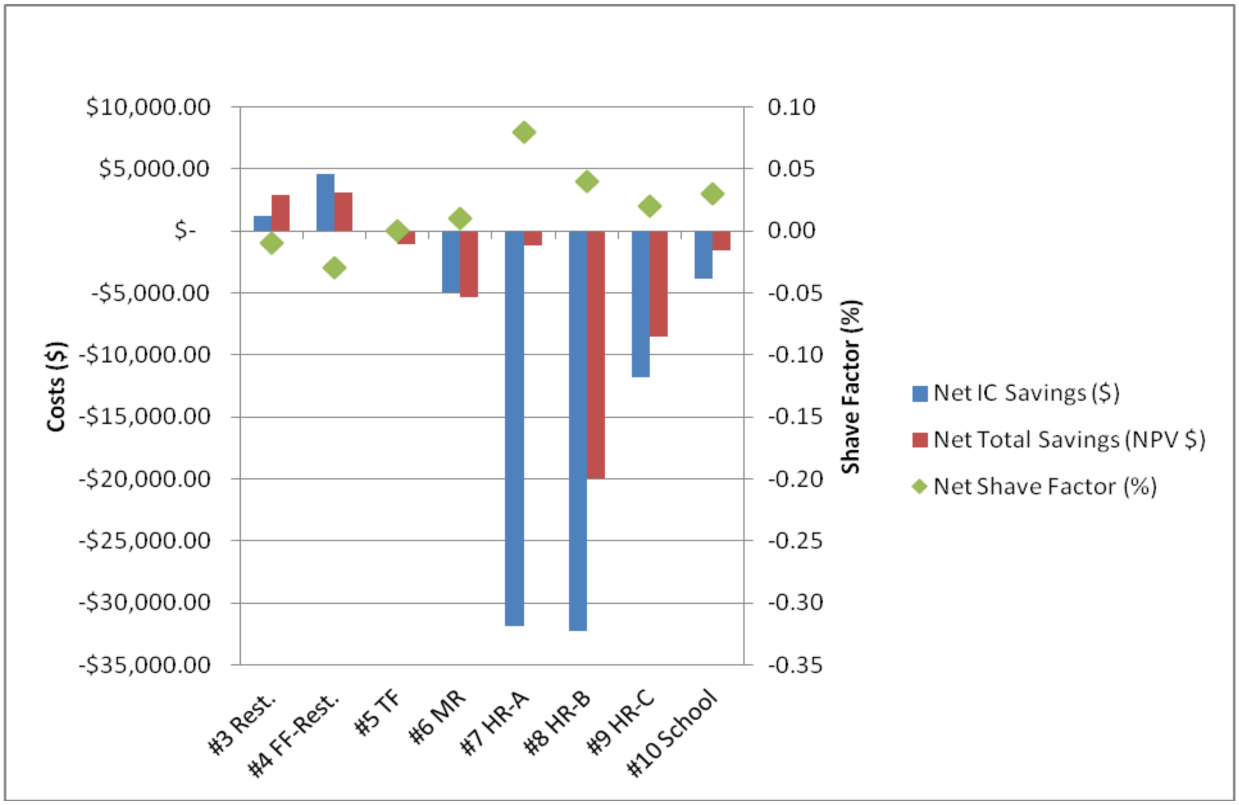


Figure 2: Fixed vs. TOU Electricity Rates

Table 8: Payback Periods – Toronto Fixed Electricity Rates

| | Building | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **#3 Rest.** | **#4 FF-Rest** | **#5 TF** | **#6 MR** | **#7 HR-A** | **#8 HR-B** | **#9 HR-C** | **#10 School** |
| **ΔPBP (Years)** | **-0.8** | **-0.5** | **0.1** | **-0.4** | **-1** | **0.6** | **0.1** | **3.9** |

## 4. Test #2 - weather sensitivity analysis

A weather sensitivity analysis was conducted using weather data from other North American cities; a total of 11 US locations focusing on weather extremities. Until this point, Toronto's fixed rates had been used and are considered here for comparison.

The hourly cooling and heating demands for buildings #1-6 and #10 were simulated in eQUEST using the TMY3 weather data [4]. Table 9 presents the operating conditions and costs used in this analysis. The ground temperatures (Table 10) corresponding to each of the 11 locations are approximated using the *long-term averages of annual average temperature* retrieved from [8].

Table 9: Operating Conditions and Costs - Weather Sensitivity

| | |
|---|---|
| Operating Duration | 20 years |
| Ground Temperature | Variable |
| Natural Gas | $0.35/m³† |
| Electricity Fixed Rate | $0.17 /kWh† |

†Data courtesy of CleanEnergy™

Table 10: Ground Temperatures [8]

| **Location** | **Ground Temperature (°C)** |
|---|---|
| Phoenix, AZ | 23.94 |
| Fresno, CA | 18 |
| Denver, CO | 9.78 |
| Miami, FL | 25.11 |
| Atlanta, GA | 16.61 |
| Honolulu, HI | 25.39 |
| Charles, IA | 8.17 |
| Kearney, NE | 9.72 |
| Portland, OR | 12.5 |
| Austin, TX | 19.61 |
| Hanksville, UT | 12.89 |

With varying weather patterns, the savings can be compared as follows:

$$\Delta \text{Total Savings} = (\text{Total Savings})_{\text{Other}} - (\text{Total Savings})_{\text{Reference Location}} \quad (7)$$

$$\Delta \text{IC Savings} = (\text{IC Savings})_{\text{Other}} - (\text{IC Savings})_{\text{Reference Location}} \quad (8)$$

$$\Delta PBP = (PBP_{\text{Optimal Design}})_{\text{Reference Location}} - (PBP_{\text{Optimal Design}})_{\text{Other}} \quad (9)$$

$$\Delta SF_{\text{Optimal Design}} = (SF_{\text{Optimal Design}})_{\text{Other}} - (SF_{\text{Optimal Design}})_{\text{Reference Location}} \quad (10)$$

The results are compared to Toronto's weather patterns (reference location). Based on equations (7) to (10), the alternative location is more economical than Toronto if values for ΔTotal Savings, ΔIC Savings or ΔPBP are positive. For the case of ΔSF, a positive value indicates the GSHP size for the building in the alternative location is larger than for the equivalent building in Toronto.

In the following figures, only buildings with an optimal SF produced by the methodology are plotted. Since the hospital and office were heating dominant in Toronto's weather with no SF, these buildings will be discussed separately. Based on the results, weather patterns have a strong effect on payback periods and costs. In warmer weather there's a larger IC savings, which contribute to a net positive total savings (Figure 3). This was achieved by downsizing the system to meet less of the peak demands (Figure 4).

There are several factors contributing to smaller SF. Firstly, in warmer weather (states: AZ, FL, HI) the average ground temperature is significantly higher than that of Toronto. As a result, a larger ground-loop length is required to meet the buildings' energy demands. In Figure 5, the fast-food restaurant requires up to a ~70% longer ground-loop in order to provide 100% of the building's total energy demands (SF=1) compared to Toronto. For a larger building such as the school, it requires a 140% longer ground-loop if Arizona's weather patterns was used.

Although buildings require more cooling in warmer weather, higher ground temperatures made downsizing the ground loop length more economical. Based on California's and Atlanta's mild winter, heating demands are kept at a minimum, which helps to produce large saving compared to Toronto. Denver, Charles and Kearney have similar weather patterns to that of Toronto's. As a result, the net change in ground loop length, savings and PBPs (Figure 6) were insignificant. Using Toronto's heating and electricity costs no SF exists for Phoenix, Miami and Honolulu (uneconomical to install GSHP system). A more detailed study considering local utility costs is warranted.

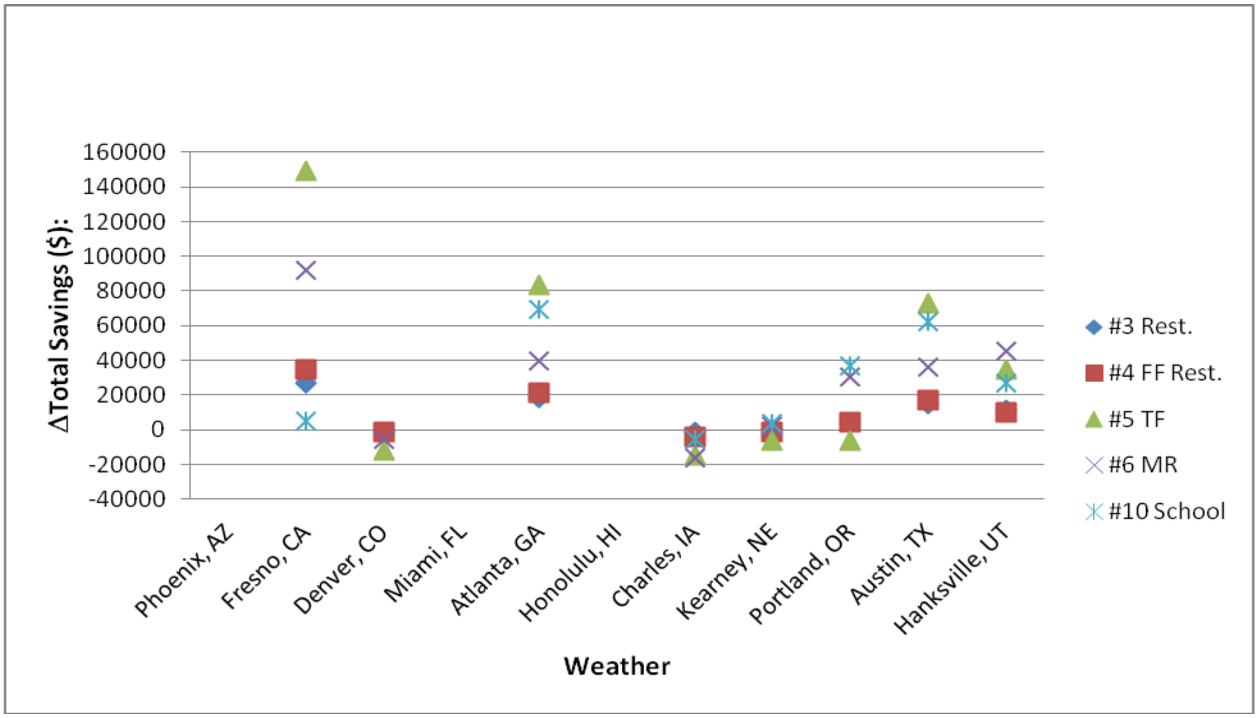


Figure 3: ΔTotal Savings: Variable Weather, Toronto Rates

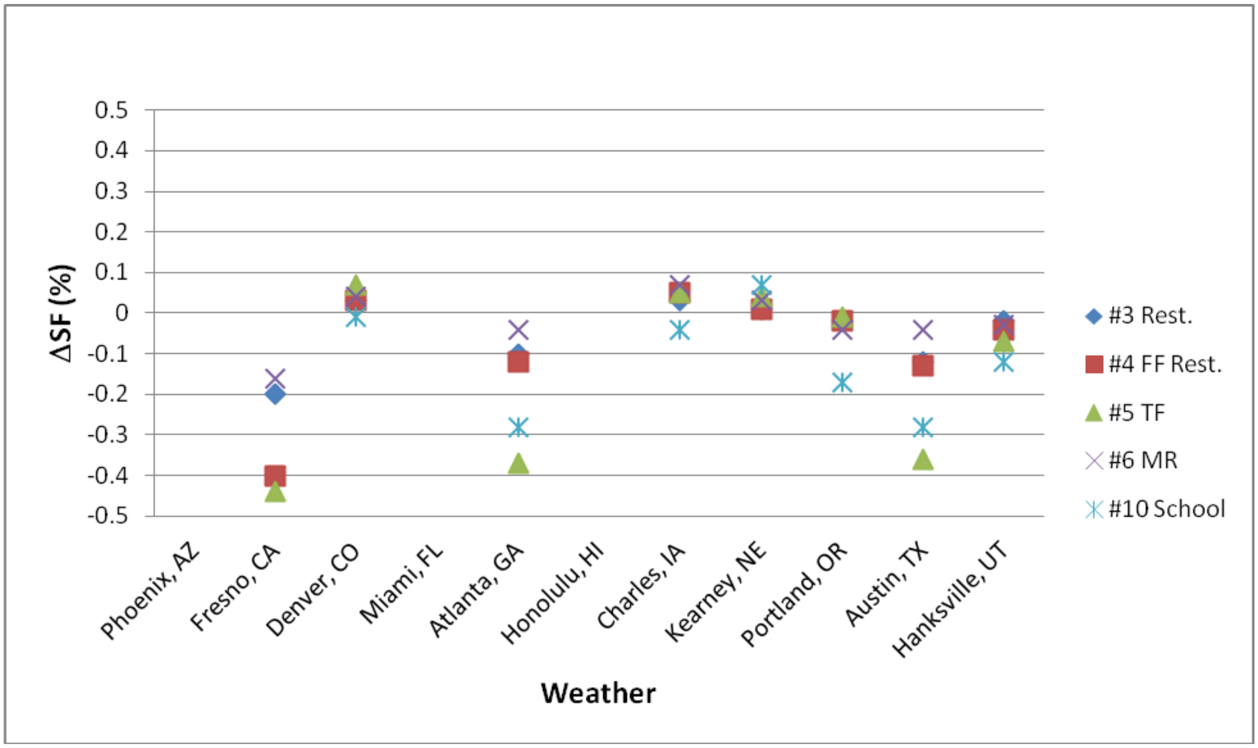


Figure 4: ΔSF: Variable Weather, Toronto Rates

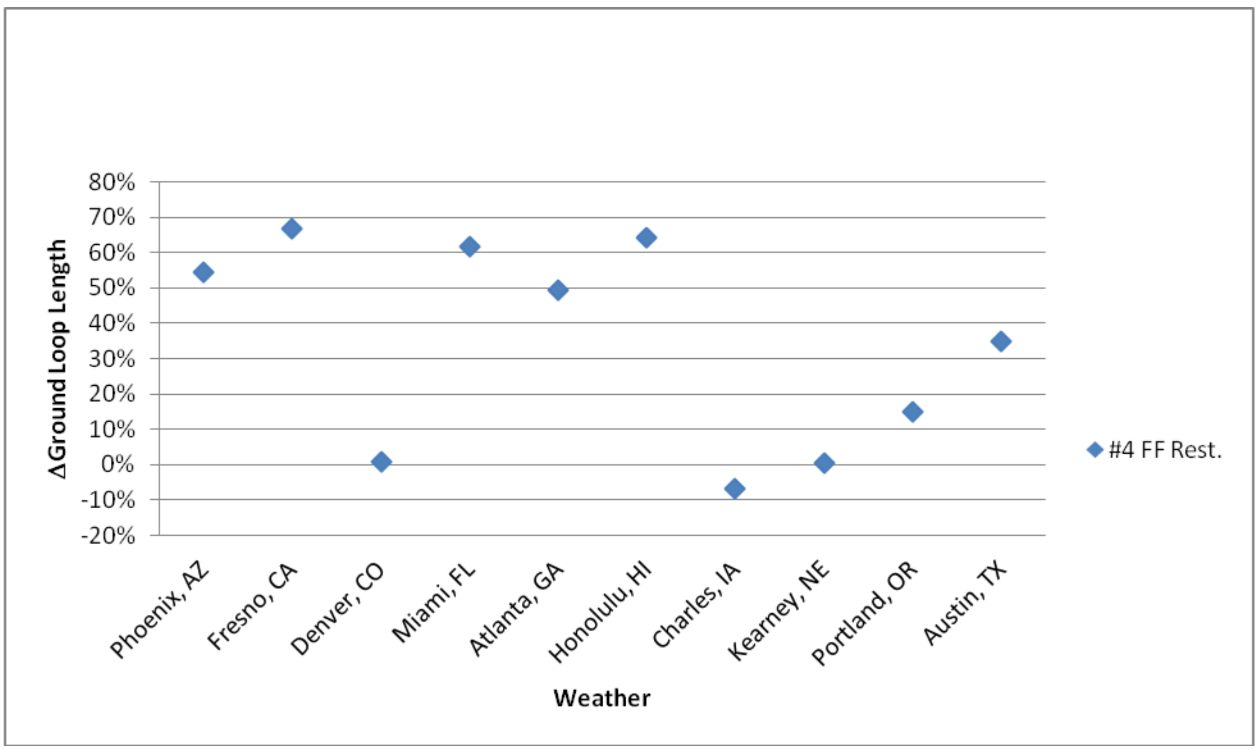


Figure 5: ΔGround-Loop Length - Fast Food Restaurant

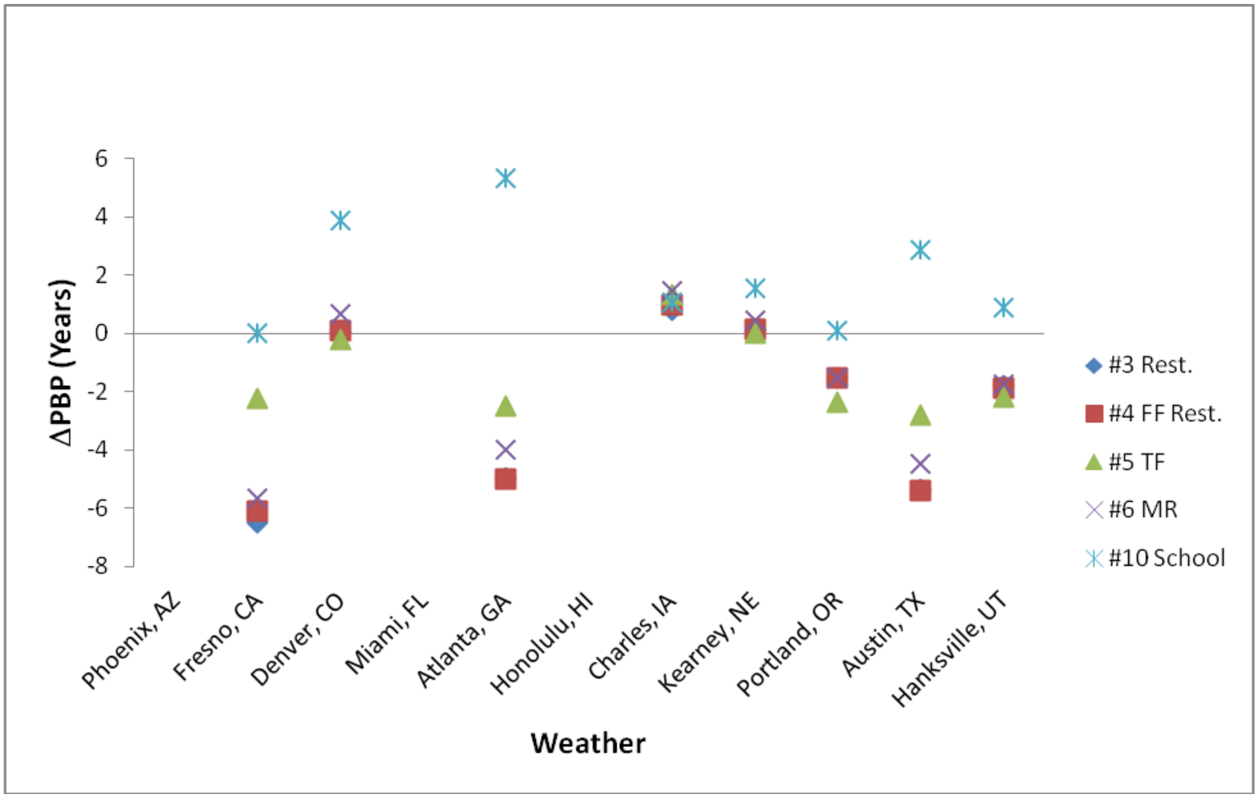


Figure 6: ΔPBP: Variable Weather, Toronto Rates
**Note: Positive values represents a shorter PBP*

It is interesting to note some unique cases where a very small optimal SF produces significant savings compared to the standard SF (Table 11). With a SF of 0.09 and 48% TEDM, the office with Austin TX's weather patterns using Toronto's rates produces significant savings compared to a SF = 1. Half of the building's energy demands are met, requiring only 13% of the ground-loop length. In all the cases, the PBPs are significantly less compared the case of SF=1.

Table 11: Low SF Cases vs. Standard SF

| Building (Weather Patterns) | Optimal SF | TEDM (%) | Total Savings ($) | IC Savings ($) | PBP (years) | PBP SF=1 (Years) |
|---|---|---|---|---|---|---|
| Hospital (Atlanta, GA) | 0.14 | 44 | 117,411 | 236,463 | 12.2 | 30.6 |
| Hospital (Portland, OR) | 0.14 | 61 | 88,324 | 146,225 | 12.8 | 36.5 |
| Office (Austin, TX) | 0.09 | 48 | 1,014,326 | 1,440,203 | 8.0 | 29.1 |
| School (Austin, TX) | 0.08 | 28 | 124,376 | 278,055 | 12.9 | 31.3 |

## 7. Conclusion

Using this methodology, the installer reduces the likelihood of overlooking a feasible installation, such as cases where the optimal SFs are small. Sizing according to rules-of-thumbs does not always correspond to an optimal design. In some cases like that of the office, an optimal design exists which is not obvious when using current rules-of-thumbs. By using the prescribed methodology, uneconomical installations can be prevented or consulted to risk averse clients.

In addition to pointing out the importance of considering TOU rates, several key findings were observed in this study. Firstly, if an optimal SF exists, its savings and PBP will be better than the SF sizing standards currently being used. Secondly, despite greater cooling needs, extremely cooling dominant buildings had longer PBPs in weather warmer than Toronto (i.e. California, Georgia, and Hawaii). This is due to the higher ground temperatures which require a larger ground loop to meet the buildings' energy demands. GSHP installations are uneconomical in Toronto for heating dominant buildings due to current low natural gas prices.

In conclusion the economic viability and optimal design of a hybrid GSHPs is highly dependent on weather and operating costs (including TOU rates). Thus further market penetration requires GSHP technology to improve in performance and a robust sizing methodology as that of [3]. The methodology should also be capable of integrating customizable control strategies and combining GSHP systems with other technologies.

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