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Underground buildings

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This paper summarizes the many potential benefits and drawbacks associated with underground buildings, while discussing the effects different functions and underground building concepts have on them. Some design strategies are identified to alleviate the negative psychological and physiological effects. The main objective of this literature study is to perform as a fundamental basis for the practical part of the research, which involves building performance simulation to assess the sunlight penetration and quantification of the thermal advantages concerned with underground buildings.

II. Underground buildings - Potential in terms of energy reduction
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Underground buildings are pointed out as an alternative to conventional aboveground buildings for reducing the total energy requirements, while alleviating land use and location problems. This paper investigates the potential in reducing the energy demand of underground buildings compared to aboveground buildings. Monthly calculations based on EN-ISO 13790 are performed to obtain the annual energy demand of an aboveground building and underground building. By comparing the annual energy demands for different climates, building functions and underground depths, deductions can be made to quantify the energy reduction potential of underground buildings. Introducing variable input parameters allows identification of the influence of design options on the annual energy demand of a building. Results identify that a variety of the underground building cases can almost be considered to be zero-energy buildings (annual energy demand below 10 kWh/m^{2}a). In contrast to the aboveground counterpart where the energy demand is up to 100 kWh/m^{2}a higher. The low annual energy demand for these underground building cases originates from the balancing energy flows. The transmission losses of the underground building are at a stable value annually in comparison to the aboveground situation, where it varies with seasonal weather changes. Underground buildings can help to reduce the energy demand in comparison to a conventional aboveground building by using beneficial soil temperatures and large amounts of earth cover as insulation. Energy reduction is achievable for all climates and functions, but the magnitude is related to the combination of different design elements. Sensitivity analysis shows that building functions with high internal gains induce an inefficient balance in tropical to warm climates for underground buildings, but strongly reduce the heating demand in cold climates. Furthermore, ground properties have a small influence on the energy demand of an underground building.

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I. Underground buildings
Comparative analysis using literature

Underground buildings
Comparative analysis using literature

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ABSTRACT: This paper summarizes the many potential benefits and drawbacks associated with underground buildings, while discussing the effects different functions and underground building concepts have on them. Some design strategies are identified to alleviate the negative psychological and physiological effects. The main objective of this literature study is to perform as a fundamental basis for the practical part of the research, which involves building performance simulation to assess the sunlight penetration and quantification of the thermal advantages concerned with underground buildings.

KEYWORDS: earth scrapers, subterranean, underground, building, architecture, earth sheltered, subsurface, earth-sheltered.

1. INTRODUCTION

The pressing problems that mankind are faced with this century and perhaps the following centuries are the energy crisis and the increasing housing demand caused by the continuous growth in the world's population. Innovative solutions such as building underground are identified as an alternative to conventional aboveground buildings for reducing the total energy requirements, while alleviating land use and location problems. When designing these structures, it is important to recognize the potentially negative psychological and physiological effects associated with underground spaces.

This literature study summarizes the potential benefits and drawbacks of underground building and how functions and different building types can affect them. Several design techniques are also identified to alleviate negative psychological and physiological concerns. While a framework is created that will assist in the practical part of this research, where building performance simulation is used to assess the sunlight penetration and quantification of the thermal advantages of underground building.

2. UNDERGROUND BUILDING CONCEPTS

A wide variety of approaches exists within the concept of underground building. At one extreme, a building can be erected on the original surface of the ground (i.e. at grade) and then be covered by earth to shelter the building partially or completely. At the other extreme, the building is constructed in a completely excavated site (i.e. below grade) [1]. In between there are several different other types of underground building concepts that can be distinguished as shown in **Figure 1**, this does not include every design possibility, but gives a typological overview. Using this classification an evaluation can be made on their effectiveness of energy reduction while maintaining indoor environmental quality. For example, a higher energy reduction can be achieved with a fully underground building, but this makes it more difficult to maintain the indoor environmental quality. The relationship between the underground building concept and these two factors is also highly dependent on the function of the building and the climate in which the building exists.

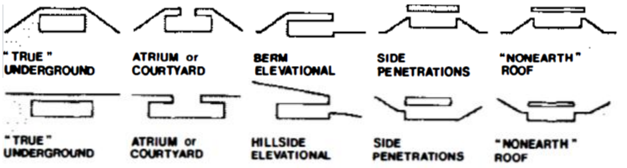


Figure 1: Classification of different underground building concepts [1].

2.1. Fully underground spaces

These spaces have little or no contact with the outside world. They can be either deep under the earth or just below the surface. Generally, only the entrance will be aboveground. In principal, these spaces have a mechanical supply of light and air. The absence of natural light and views makes prolonged stays underground less appealing.

Fully underground buildings are comparable to buildings without sunlight above ground, and there are several examples of those. People love to shop in the familiar closed boxes of Ikea, department stores and do-it-yourself shops. Many people also work in such introverted environments. Most industrial estates, where the working population spends much of its time, are full of enclosed buildings [2].

2.2. Submerged spaces

Submerge spaces are those lying just under the surface of the ground. They can extend deep into the ground but they always have direct contact with the aboveground world and with natural light. To admit daylight, the surface of the ground is perforated by patios, atriums and domes. An atrium can transport daylight to great depths, providing not only natural light, but also some external views. In any event, a view of the sky provides contact with the seasons, the weather and the time of day.

2.3. Earth-covered spaces

An earth-covered building is not underground, but rather at grade, with a surface laid over it. This building type is free of the technical disadvantages of underground building, while enjoying its spatial advantages. Daylight can penetrate normally and views are usually unimpaired. The elevated ground level can be laid out as a park, landscape, or urban environment. In the majority of cases, earth-covered buildings can be constructed in the traditional manner. Only the roofing and cladding of one or more facades is essentially different [2].
Constraints such as a high water table, expansive clay soils, rock strata, or flat rural sites have often been overcome with an at grade concept [1].

In practice, all three types are found in all kinds of combined forms as shown in **Figure 1**. Underground buildings are generally connected in one way or another with aboveground buildings, may it be for the entrance to the building or a larger part of the building that is situated aboveground, in the latter the underground part is generally referred to as its cellars or basement [2].

As indicated, underground buildings have widely varying characteristics and are therefore very dependent on the building type. Some basic assumptions about the most important characteristics of underground buildings must therefore be made when discussing the advantages and disadvantages. They are discussed below, followed with a summary in **Table 1**, where a division is made between major issues and is grouped in categories.

3. Benefits of underground building

The benefits offered by underground structures are based on certain specific qualities of underground space and the fact that they are isolated from the surface to some extent.

3.1. Benefits with regard to energy use

In general, the greater the percentage of surface area in contact with the earth and the deeper the structure penetrates into the earth, the more the structure will benefit in terms of energy conservation [3]. However, for many functions direct access to the surface and window openings are required for a variety of psychological, physiological, and safety reasons. Energy related benefits are therefore constrained by the requirement for these openings, as well as by the structural costs of supporting extensive earth loads at greater depths [3]. Some assumptions and measurements on the energy consumption can be found in the literature, but are not coherent and vary in large amounts due to the different underground building concepts.

3.1.2. *Reduction of conduction*

A popular misconception about earth is that it is a good insulator. However, earth is a poor insulator, particularly when compared to commonly available insulating materials used in building constructions. But even a poor insulating material can insulate effectively if it is massive enough. The fact that heat loss must flow vast distances makes earth a suitable blanket in which to wrap a building [4].

3.1.3. *Heat storage capacity*

The heat storage capacity of an underground building, due to the high thermal mass of the structure and the surrounding earth, is another important characteristic. The thermal mass of a structure is a function of the density and quantity of the building materials combined with their ability to store heat. Any building with a large thermal mass absorbs heat from the air or from direct solar radiation and releases it back into space at night, when there is a net heat loss. In an underground building, which has a high thermal mass this process can be slow enough to “carry” the house for several hours without any heating from an additional source. In contrast, conventional dwellings can store very little excess heat and lose whatever heat they have relatively fast when the source is interrupted [5].

3.1.4. *Stability ground temperatures*

Due to the relatively stable temperature of the soil, the underground building in summer loses heat to the cool earth rather than gaining heat from the surrounding air, and in winter the relatively warm soil offers a much better temperature environment than the subzero air temperatures [5]. Energy is needed only to overcome the difference between the earth temperature and a comfortable temperature, thus flattening the peak energy requirements for space conditioning. In essence, the earth moderates the environment in which the building is located [4]. The potential to save energy depends on the ground temperatures surrounding a building which is affected not only by climate, but other factors such as ground cover, soil moisture content, and heat from adjacent buildings [3]. The greater the depth the more stable the soil temperatures become, while peak temperatures occur after a considerable delay [3]. Insulation, which separates the interior space from the earth, reduces the cooling effect, but also the effective release of heat to the ground.

3.1.5. *Control on air infiltration*

Another factor in saving energy through earth sheltering is the reduction of infiltrated outside air. With the earth covering most of the envelope of a building, the building can be made more airtight. In surface structures, up to 35% of heat loss can often be attributed to air infiltration [4], while for building surfaces in contact with the earth, infiltration is completely eliminated resulting in both heating and cooling load reduction. However, too "tight" construction can cause the build-up of indoor air pollutants, which some experts say can be far unhealthier than the worst outdoor urban smog. An underground building offers greater opportunity to control the rate of outside air supply to the interior of a building [4].

3.1.6. *Reduction of heat gain*

Earth-covered roofs and walls reduce radiant heat gain from the sun. The massive earth can absorb a considerable amount of radiation before it reaches the envelope. While window area of most underground buildings is minimized by design, a major source of heat gain in many aboveground buildings is reduced considerably [3]. Another very important component in reducing heat gain from radiation is the use of plant materials. In the process of evapotranspiration, plants can effectively cancel out most of the incoming radiation from the sun. This requires a sufficient level of moisture in the ground to enable the plants to grow [3].

3.1.7. *Impact of occupancy patterns on energy related benefits*

Many of the energy related benefits are associated with heat transfer through the exterior skin of the building. The relative importance of the exterior envelope of the building in terms of heating and cooling loads depends on the occupancy patterns and use of the structure. For functions with a relatively high number of people, ventilation requirements are greater and usually internal heat gain from lights, people, and machines are increased as well. Thus, the functions that can benefit to the greatest extent by being underground are those with low to moderate occupancy levels. These include warehouses, cold storage, archives, laboratories, recreational facilities, parking, and some offices and libraries. An overview of different functions and their impact on characteristics of underground buildings is given in **Table 4**. However if heat transfer through the exterior envelope of a building is not large relative to ventilation and internal heat gains, it may still represent a substantial amount of energy [3]. In addition, as ventilation and lighting systems become more energy efficient, the relative importance of energy transfer through the exterior skin will increase.

Not only the number of people in a space but also the patterns or timing of that occupancy, affect energy usage. Some buildings must be operated 100 percent of the time, whereas others have sporadic or intermittent use.

3.2. Benefits with regards to land use and location

In many cases, underground spaces result from a lack of surface space or location problems, several benefits are mentioned.

3.1.1. *Limited visual impact*

Partially or completely underground buildings are less visible than above-grade buildings, which can be an advantage in a number of situations. For example an underground building can preserve the character of sensitive sites with natural beauty, where man-made structures may be undesirable. Or in a similar way, an underground building is often an appropriate solution for an area with a special historical character where an above ground contemporary building would be disruptive [3]. Many other buildings are unwanted above ground due to their physical appearance and therefore are necessarily placed underground, for example; public utilities, storage of less-desirable materials and car parks.

3.1.2. *Preservation of surface space*

By placing a building underground and by allowing the roof to remain as a park or plaza area, no open space is lost. This is very beneficial for compact building areas with limited remaining open space. Not only is this space desirable for recreation, but it can also relieve the feeling of density and allow greater access to sunlight and view for above ground buildings [3].

3.1.3. *Efficient use of scarce land*

The use of underground space allows a building to be built in a location where this is not possible on the surface, either because of lack of space or because it is not acceptable to the community. Extensive amounts of space can be created without requiring additional land, while unique and efficient functional relationships could be developed, such as housing on the surface with workplaces in the mined space below, or commercial uses on the surface with manufacturing, storage, and service below. Such relationships can create compact, efficient development patterns within urban areas while preserving agricultural and recreational land by reversing the trend toward sprawling development [3].

3.1.4. *Topographic reasons*

In hilly or mountainous areas, the use of tunnels improves or makes feasible various transport options such as roads, railways, canals, etc. Tunnels are also an important option in river, streets and harbor crossings. Generally speaking, underground space use offers many advantages with regard to the layout of facilities and infrastructures. These advantages derive essentially from the freedom (within geological, cost, and land ownership limitations) to plan a facility in three dimensions and from the removal of physical barriers on the land [6].

3.1.5. *Preservation of natural vegetation/scenery*

A well designed earth sheltered building can blend with the surrounding earth and become part of the natural landscape. In addition to the positive aesthetic effect on the environment, underground buildings provide the opportunity to improve or enhance the natural environment, particularly in urban areas [3]. Another benefit is the revitalization of the natural landscape that results simply from the increase in the amount of plant and animal habitat in a given area. Water and air quality are enhanced and the soil is enriched by allowing the natural ecological processes to occur within the boundaries of a built environment [3].

3.1.6. *Fire protection*

Underground structures are mostly built of concrete surrounded by soil or, in the case of mined space, rock caverns. These fireproof materials provide a great degree of fire protection and prevent the spread of any fires to or from other buildings [3]. In spite of the fireproof nature of underground buildings, materials within the buildings may still be combustible. Since these structures often have fewer openings to the surface and the path of exit for occupants is upward rather than downward, some unique life safety problems may arise. Careful design and consultation with building code authorities is necessary [3].

3.1.7. *Protection from surface noise and vibration*

Small amounts of earth cover are very effective at protecting from the transmission of airborne noise. Similarly, if the vibration sources are at or near the ground surface, levels of vibration will diminish rapidly with depth below ground and distance of the source [7]. This could be desirable for two reasons. First the function to be enclosed may require quiet and isolation from the surrounding environment. Where a second reason is that the function itself creates undesirable noise and the outside environment would benefit from any reduction in the noise. Manufacturing facilities or transit systems are examples of such undesirable functions [3].

3.1.8. *Provide security*

Because of its isolation from the surface substantial fireproof construction, and limited points of access, underground space can be considered more secure than above ground buildings. With limited points of entry, surveillance is easier, resulting in fewer break-ins. This is a particularly appealing feature for the storage of important records, manuscripts or critical materials such as emergency food and fuel supplies [3].

3.1.9. *Protection from natural disasters*

Underground structures are naturally protected from severe weather (hurricanes, tornadoes, thunderstorms, and other natural phenomena). Underground structures can also resist structural damage due to floodwaters, although special isolation provisions are necessary to prevent flooding of the structure itself [7]. Moreover, underground structures have several intrinsic advantages in resisting earthquake motions; they are less affected by the surface seismic waves. The structural oscillation effects are limited, since they are constrained to move with the ground motion. Besides, as they are designed to support important ground loads, they often can better resist earthquake loadings [7].

3.1.10. *Protection from cold or hot climates*

Although advantages can be achieved for reducing the energy demand when building underground, people may also benefit largely from the fact that do not have to endure extremely high or cold temperatures during the day and night, when infrastructure and other facilities are also being provided for underground.

3.3. Benefits with regards to Life Cycle Costs

3.1.1. *Reduced maintenance*

Reduced maintenance is needed for underground buildings in comparison to conventional buildings at grade. This premise is based on the earth sheltering effect on much of the exterior building envelope. Therefore, the building is less likely to be weathered by various climatic elements. Consequently, all earth-contact components of the structure will be protected from wind, rain, heat, hail, freezing, thawing, and other natural causes. This entails no shingles blown off in a storm, very little painting required, water pipes never freezing, and permanently clean gutters. Aboveground buildings are also exposed to intense heat and ultraviolet solar radiation in hot climates, which causes surface fading and discoloration of exterior painting [8]. Ultraviolet radiation also degrades roofing materials such as the waterproofing membrane [9].

3.1.2. *Building and building material durability*

The daily extreme temperatures and temperature differences existent in extreme climate can be destructive to buildings and building materials because of the daily expansion and contraction of the exposed surfaces. Especially where there are different expansion rates [9]. The benign conditions under soil cover increase the structural longevity of building materials, which are protected from the various exposed conditions in harsh climates and its weathering effects.

3.1.3. *No need of external cladding*

Dependent on the amount of surface area in contact with the air, the need for external cladding is reduced. Cladding and finishes typically account for about 15% of a building’s cost and providing a watertight exterior is usual one of the key milestones in the construction program, on which many other activities rely [10].

4. Disadvantages of underground building

The fact that underground buildings are more isolated from and less exposed to the surface presents some design problems. The extra cost of resolving these difficulties along with other technical problems can present drawbacks compared with above ground construction [3].

It is interesting to see that some of the greatest drawbacks are not physical or technical in nature but are psychological [3].

4.1. Disadvantages with regard to energy use

Energy related benefits discussed in the former paragraph have in addition potential limitations. These limitations are very much dependent on the individual design of the underground structure and specific climate conditions.

4.1.2. *Impact of ventilation rate*

One of the basic characteristics relating to energy use in buildings is the ventilation rate required by the building code to provide a healthy, pleasant environment. The amount of fresh air to be brought into the buildings is a function of the number of people occupying it and therefore related to the function of the building. Although large benefits are obtained from minimizing both transmission and infiltration losses through the exterior skin of the building, in building with high ventilation rates, the energy saving is somewhat diminished when large amounts of outside air are to be introduced into the building [3]. No use can be made of natural ventilation, while ventilating mechanically at a larger depth consumes more energy.

4.1.3. *Requirement for openings*

A windowless underground space is unsuitable for many functions. The various requirements for access, window openings, and other exposed portions of the building envelope diminish the area of the envelope in contact with the ground, which break the continuity of the earth mass surrounding the building, thereby diminishing the energy-conserving benefits related structure-earth benefits.

4.1.4. *Slow response*

Although the mass of the concrete structure surrounded by the earth mass are beneficial in many ways, they result in a structure that cannot respond quickly to changed conditions. This means that some strategies, such as night setback, may not work effectively or may work only with an unsatisfactory time lag. This gives also problems for situations where extreme loads such as overheating from a large crowd in a theater or auditorium.

4.1.5. *Lack of useful ground temperatures*

Underground buildings in climates needing the most heat have the lowest ground temperatures and buildings in climates that need cooling have the highest ground temperatures. The influence on the ground temperature is more significant for extreme temperature fluctuations and therefore most benefits are likely to be obtained in climates with great daily and seasonal fluctuations [3]. It should be noted that the ground temperature deficit is less significant at a greater depth, which will create a more stable indoor environment.

4.1.6. *Heating/cooling compromises*

Although an underground building offers potential benefits in both the heating and cooling seasons, maximizing these benefits requires insulation in the heating season, but direct earth contact with no insulation in the cooling season. In some cases the necessary compromise prevents optimizing for either condition alone [3].

4.2. Disadvantages with regards to land use and location

4.1.1. *Water problems*

An underground building has a greater potential for water leakage problem than a typical aboveground structure. This is particularly true if the underground structure is partially beneath the subsurface water table [3]. All underground buildings therefore require a high-quality waterproofing system regardless of the site drainage or depth of the water table.

4.1.2. *Protection of the underground environment*

The use of underground space is irreversible. Unlike constructions aboveground, that can be demolished and rebuilt differently. This irreversible aspect of using underground space is a major consideration when developing this space and explains its specificity. It is therefore important to avoid "consuming" it in an uncontrolled and unplanned manner [7]. The vulnerability of ground water tables is the most characteristic aspect of the fragility of underground space. Any use of underground space that affects formations located below the ground water level can have an impact on the quality of underground water tables or their flow, or on both [7].

Any underground excavation has effects on the surrounding geological environment, whose natural constraints are inevitably altered. The geological environment is permanently marked by developments made in it, and there is no way of re-establishing its initial conditions. Moreover, if this phenomenon of "decompression" is not controlled, it can have harmful consequences for the stability of adjacent structures [7].

4.1.3. *Lack of available data on the energy performance*

There is a lack of available data on the energy performance of underground buildings, which makes it difficult to support the advantages of it in a concrete way. As predicting the overall performance of underground buildings is difficult due to the behavior of unknown, long-term soil temperature changes in some regions and heat flow through walls and soil [9], [3].

4.3. Psychological and Physiological considerations

4.1.1. *Lack of natural light*

The lack of natural light is one of the most often mentioned negative characteristics of underground space. Access to natural light is important to users of a building even if the proportion of daylight to artificial lighting for work tasks is relatively low. The feeling produced by daylight to artificial lighting for work tasks is relatively low. The feeling produced by daylight, its variability, and the sense of contact with the outside world are important reasons for its desirability. Another important positive psychological association of natural lighting is that sunlight connotes warmth [11].

4.1.2. *Lack of exterior view*

The lack of exterior view from an underground space is another reason for dissatisfaction with this type of building. In addition to providing natural light and sunlight, windows provide a direct view for observing weather conditions, create a sense of contact with the environment, and giving visual relief from immediate surroundings [11].

4.1.3. *Lack of spatial orientation*

A windowless building also induces a lack of spatial orientation since exit points are not visible, creating a fear of not being able to escape in an emergency.

4.1.4. *Negative psychological reactions*

Some people have a strongly adverse reaction when underground buildings are mentioned. They have subconscious negative feelings about them [3]. Several reasons have been suggested for this phenomenon:

- Association with death and burial;
- Fear of collapse or being trapped;
- People also associate underground spaces with poorly designed and ventilated basements which are damp and unpleasant;
- Feelings of claustrophobia may occur due to the absence of windows for direct contact to the outside environment and the subsequent lack of stimulation from the variety of changing weather conditions and sunlight.

4.1.5. *Lack of fresh air/indoor air pollution*

The earth covering the underground buildings eliminates most of the causes of air-infiltration because of its tight construction. A well designed underground building should therefore include a ventilation system so that stale air can be exhausted and fresh air is added at a sufficient rate.

4.1.6. *High humidity/Condensation*

Surrounding earth is almost always cooler than the indoor air temperature, condensation on interior surfaces may occur. Problems are dependent on the local climate as well as on the manner in and degree to which outside air is introduced into the building [3].

4.1.7. *Excessive noise or lack of noise*

Due to the mass of the earth sound insulation is exceptionally high; the only significant sound transfer is via entrances and exits into buildings and ventilation installations. This causes noise from equipment inside to be a nuisance.

4.1.8. *Lack of public acceptance*

A great hindrance to the consideration of underground building is that planners think the public will not accept living in underground building [12]. However, it is thought that the public will accept underground building if they are educated on the benefits of these structures [12].

4.1.9. *Radon concentration*

No style of building is more vulnerable to radon penetration than one built with total contact with the soil. Radon-proofing is possible both before and after construction, but no underground buildings should be built in any radon risk area without anticipating radon problems.

4.4. Disadvantages with regards to Life Cycle Costs

4.1.1. *Increased structural (cost) requirements*

The relatively great weight of earth on roofs with lateral earth pressures on underground walls, require heavier and more expensive structures.

For all sub-surface constructions, it is particularly important to predict the properties of the ground, because misjudgments can have serious consequences for a project as regards completion dates and additional costs. Geological surveys are therefore vital and include the development of systems for the mapping of geological, hydrological and seismologic conditions, and to make up plans for pre-investigations (seismic and other geophysical measurements, core drilling and determination of physical properties of rock) [7].

However it is not conclusive that the construction cost of every underground building will be higher than its aboveground counterpart. This area maintains a high controversy as the increased costs that occur out of necessity can often be offset by reduction in other areas [9]. For example, since underground buildings have lower heating, cooling and peak load demands, the mechanical systems can be smaller and are consequently less expensive to install, although costs for ventilation may increase. Furthermore, reduction in a thermal load also results in less cost for thermal insulation requirements. With much of the building’s facades in contact with soil, exterior finishing costs are also reduced. Even if there is some doubt in the literature as to the initial cost of underground building, there is no disputing that there are large savings in the long term [13], [14].

5. Efficient designing

As shown in **Figure 1** underground buildings are not limited to any fixed design solutions. There are many different concepts that can be applied, where one is preferred over the other dependent on the climate, function and location of the building. To make a comparison between the advantages and disadvantages concerning different underground building concepts, a matrix is created as shown in **Table 2**. It should be mentioned that the effects of different climates and functions are not taken into account here and will be discussed later on. Ratings are given based on an analytical review of existing literature to note the differences.

For example, the greater the percentage of surface area in contact with the earth and the deeper the structure penetrates into the earth, the more the structure will benefit in terms of energy conservation, while this has negative effects on psychological and physiological aspects [3]. In this way of thinking, it is clear that a fully underground building is better suited for reducing energy than an underground building with site penetrations.

Table 1: Benefits and drawbacks of underground facilities (adjusted from [15]).

ISSUES	CATEGORY	POTENTIAL BENEFITS	POTENTIAL DRAWBACKS
PSYCHOLOGICAL & PHYSIOLOGICAL	PSYCHOLOGICAL	Relief from severe climate (coolness in hot-climates)	Lack of spatial orientation Negative psychological reactions association death and burial, claustrophobia, fear of collapse/entrapment Lack of public acceptance
	PHYSIOLOGICAL	Isolation from surface noise and vibration Stable indoor temperatures	Excessive noise or lack of noise Lack of fresh air/indoor air pollution High humidity/condensation Lack of natural daylight and view Higher radon concentration Requirement for openings
ENERGY	ENERGY USE	Reduction conduction Heat storage capacity Stability ground temperatures Control on air infiltration Reduction of heat gain	Impact ventilation rate Slow response Lack of useful ground temperatures Heating/cooling compromises Lack of available data on the energy performance
LAND USE AND LOCATION	PROTECTION	Provide security limited access Fire protection Protection from severe climate Protection from natural disasters	Degradation underground environment
	LOCATION	Visual impact Preservation of surface space Lack of surface space Preservation of natural vegetation scenery/ecology Efficient use of scarce land	Aesthetics skillful design, building services Uncertain geology Unfavorable geology
	LAYOUT	Topographic freedom	Access limitations Sewage removal Water problems Adaptability
LIFE CYCLE COSTS	INITIAL COST	No need of external cladding Land cost savings No structural support, Weather independent	Increased structural cost requirements Ground excavation Cost uncertainty Confined work conditions Ground support
	OPERATING COST	Reduced maintenance Building and building material durability Energy use Insurance	Personnel access Ventilation and lighting

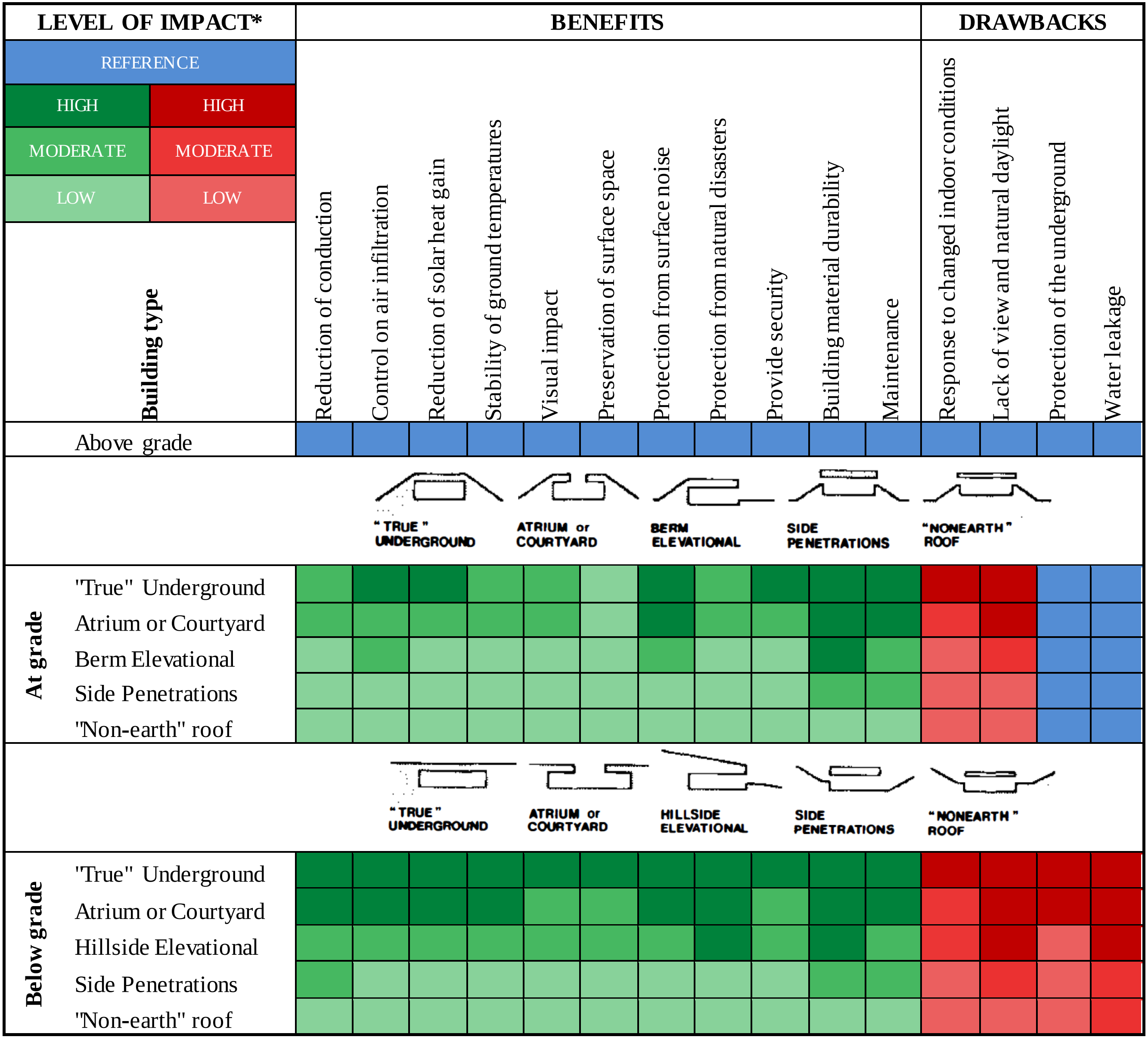
6. Functions

Underground functions are becoming increasingly diversified. Spaces for working, shopping, leisure and even living are appearing alongside traditional storage and transport functions. The demands made on the space vary for each individual function, whereby the length of time spent underground plays an important role.

6.1. Living

“Habitation is the most difficult function to place underground. Contact with the upper world, with light and air is so important that rules concerning such aspects are generally specified legally. With a little ingenuity, submerged buildings are able to comply with such regulations. Underground homes are introverted by definition, and are comparable with patio homes, which appeal only to a limited group of consumers. There are more points of contact with earth-covered homes. The relationship with the outside world and the quality of life are entirely comparable with the accepted manner of house building, even where views are concerned. Certain parts of a housing program, such as storage space, garages and sanitary rooms, can be built underground without much difficulty" [2].

Table 2: Comparison of different underground building concepts and their effect on several benefits and drawbacks.



LEVEL OF IMPACT*	
REFERENCE	
HIGH	HIGH
MODERATE	MODERATE
LOW	LOW

	Building type	**BENEFITS** Reduction of conduction	Control on air infiltration	Reduction of solar heat gain	Stability of ground temperatures	Visual impact	Preservation of surface space	Protection from surface noise	Protection from natural disasters	Provide security	Building material durability	Maintenance	**DRAWBACKS** Response to changed indoor conditions	Lack of view and natural daylight	Protection of the underground	Water leakage
	Above grade	REFERENCE	REFERENCE	REFERENCE	REFERENCE	REFERENCE	REFERENCE	REFERENCE	REFERENCE	REFERENCE	REFERENCE	REFERENCE	REFERENCE	REFERENCE	REFERENCE	REFERENCE
At grade	"True" Underground	MODERATE	HIGH	HIGH	MODERATE	MODERATE	LOW	HIGH	MODERATE	HIGH	HIGH	HIGH	HIGH	HIGH	REFERENCE	REFERENCE
	Atrium or Courtyard	MODERATE	MODERATE	MODERATE	MODERATE	MODERATE	LOW	HIGH	MODERATE	MODERATE	HIGH	HIGH	MODERATE	HIGH	REFERENCE	REFERENCE
	Berm Elevational	LOW	MODERATE	LOW	LOW	LOW	LOW	MODERATE	LOW	LOW	HIGH	MODERATE	LOW	MODERATE	REFERENCE	REFERENCE
	Side Penetrations	LOW	LOW	LOW	LOW	LOW	LOW	LOW	LOW	LOW	MODERATE	MODERATE	LOW	LOW	REFERENCE	REFERENCE
	"Non-earth" roof	LOW	LOW	LOW	LOW	LOW	LOW	LOW	LOW	LOW	LOW	LOW	LOW	LOW	REFERENCE	REFERENCE
Below grade	"True" Underground	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH
	Atrium or Courtyard	HIGH	HIGH	HIGH	HIGH	MODERATE	MODERATE	HIGH	HIGH	MODERATE	HIGH	HIGH	MODERATE	HIGH	HIGH	HIGH
	Hillside Elevational	MODERATE	MODERATE	MODERATE	MODERATE	MODERATE	MODERATE	MODERATE	HIGH	MODERATE	HIGH	MODERATE	MODERATE	HIGH	LOW	HIGH
	Side Penetrations	MODERATE	LOW	LOW	LOW	LOW	LOW	LOW	LOW	LOW	MODERATE	MODERATE	LOW	MODERATE	LOW	MODERATE
	"Non-earth" roof	LOW	LOW	LOW	LOW	LOW	LOW	LOW	LOW	LOW	LOW	LOW	LOW	LOW	LOW	MODERATE

*Level of impact scaled from high to low with reference to an conventional above grade building.

6.2. *Working*

"Work areas can be located underground more readily than homes. That is why earth-covered and submerged companies and offices from diverse sectors, such as services, government, education, research, trade and production can be found everywhere. Their market values seem not to be adversely affected by being situated underground. Working areas have to comply with requirements related to indoor climate, daylight, safety, health and working hours, all laid down by law. Only limited periods of work in environments without sunlight are permitted. Submerged and earth-covered companies working space can comply with this legislation relatively easily. The demands users make of their working environment are also subject to change. For people working on computer screens in particular daylight may be disturbing. Those working in modern offices therefore prefer not to sit by the window, except when reading, during coffee breaks and in meetings. The options for entirely underground working environments are limited. unsightly closed boxes in industrial estates for labor intensive functions such as logistics, storage, automated production, utility facilities, transport and distribution can very well be built underground" [2].

6.3. Shopping

"It is much harder to move consumers vertically than horizontally. For underground shops, this means the need for a stronger crowd-puller to tempt consumers downward: what is referred to as goal0oriented shopping. Supermarkets, department stores, do-it-yourself shops and home furnishing shops are such attractions. Such large-scale retail trades can also be situated quite well entirely underground. Sufficient parking facilities in the immediate vicinity are a hard and fast precondition, while daylight is not. A combination of less compelling attractions can also succeed in enticing consumers, meaning more recreational shopping. Shops must have sufficient collective critical mass, however. Bookshops, boutiques, chemists and gift shops are not attractive enough to be situated singly underground, but in conjunction, they are. A direct connection to a metro or train station is ideal, as consumers can be drawn from passenger flows.

Integration of aboveground and underground shopping levels can result in sophisticated complexes, where consumers are hardly aware of where they. Visibility, safety and appeal are, naturally, important factors, but this is not specific to underground shops" [2].

6.4. Leisure

"Many people want to be entertained in their leisure time. Sports stadiums, cinemas, museums, theatres, libraries, amusement arcades and theme parks are just a few examples from the wide and varied range of activities available. People enjoy visiting such buildings regularly, and spend relatively long periods of time in them. From that point of view, one might assume that leisure activities offered few opportunities for using underground space. In fact since by their very nature many of these activities render daylight superfluous, if not undesirable, they offer great opportunities. Daylight is undesirable for many forms of entertainment. The emergence of the experience economy, in which people are focused on 'collecting' experiences, makes the layout of the physical space extremely important. A specific, often thematic atmosphere has to be created in the interior, for which artificial light is much more suitable than sunlight, especially when staging evocative experiences. Amusement arcades, discotheques, cinema complexes make good use of this tool. For this function, all forms of underground building are, in principle, perfectly good alternatives to building aboveground, and the easy limitation of noise nuisance can be an additional advantage.

Many museums also avoid daylight. Collections are often so light sensitive that daylight is kept to a minimum in exhibition halls" [2].

6.5. Storage

"Cellars and basements have traditionally been the storage spaces where perishable goods, wine and ice could be kept for long periods. These days, basements are used primarily for parking cars. In addition to transport, parking is the most common underground function. Public spaces are relieved of all vehicles and laid out as attractive leisure areas. Parking is not the only form of underground storage. All kinds of goods, hazardous substances, chemicals, waste, water, oil and gas are also stored here. Spatial advantages and environmental and safety aspects are often more decisive than economic considerations" [2].

6.6. Transport

"The minor infrastructure consists of cables and pipes for transporting information, energy and liquids, and has long been installed underground. Only when the street is dug up are we confronted with it. The major infrastructure, consisting mostly of roads and railway lines, is far more visible. In fact its dominance in our environment has made it a loaded subject" [2].

Table 3: Classification of underground space use in primary functions and function types.

Primary functions	**Function type**	**Example of use**
Residential	Urban/rural residential	Dwellings, Hotel, Pension
Industrial	Manufacturing Research	Sewage treatment plant, Fresh water Plant, Print shop, Laboratory, Hydro-electric power house, Ammunition plant, Assembly plant, Repair shop
Commercial	Office space	Office
	Retail	Shopping mall, Stores, Restaurant, Gas service station
Educational		Classroom, Laboratory, Library
Medical		Hospital room, Operating theatre
Religious		Church, Mosque, Synagogue
Leisure	Sports Recreation / Culture	Swimming pool, Sports facility, Mine visit, Theatre, Cinema, Museum, Bar, Disco, Library, Theme park, Amusement arcade
Storage	Hazardous material	Radioactive waste, chemicals
	Food	Wine cellar
	Natural resources	Gas, oil
	Other goods	Bank vault, Fur vault, Museum vault, Warehouse, Cold storage, Archives, Parking garage
Military	Defensive	Fallout shelters, Submarine nests, Missile silo, Strategic defense center, Prison
Utility	Passenger transport	Pedestrian tunnel, Train tunnel, Car tunnel
	Vehicular goods transport	Car tunnel, Train tunnel, Subway tunnel
	Non-vehicular transport	Aqueduct, Waste water pipes, Gas, electric, Telephone wires and Digital data (by cabling, piping, tubing), District heating system, Pneumatic system
Agriculture		Plant nursery, Mushroom growing

To analyze the use of underground space on the development of the built environment, it is necessary to differentiate possible functions of underground structures. In **Table 3** primary functions and function types are listed with several examples of use for underground structures.

In the same way as for different underground building concepts, a matrix has been created that will rate different functions dependent on the level of requirement for different advantages and disadvantages as shown in **Table 4**.

For example, there is a high requirement for utilities/storage to be underground so that they have limited visual impact, while residential buildings are designed well and are therefore aesthetically preferred. Another example is the high ventilation rate that is needed for functions that have a high occupancy rate, such as theatres, where storages require only a small amount of ventilation.

7. Measures to improve living in the underground environment.

Providing an underground environment that is as attractive as the surface environment will help eliminate psychological estrangement, resulting from being below grade, and will shorten the time required to adjust to the new surroundings. In short, the design should create a state of comfort and satisfaction for both human vision and psyche [16].

Design strategies and the application of technology can help alleviate the negative characteristics to improve living in the underground environment. The most important considerations fall into different categories.

7.1. Physiological

7.1.1. *Natural light and view*

Probably the most important physiological drawback in underground spaces is the lack of natural light. To replace day lighting and its effects, it is most desirable to replicate the spectral compositions of daylight as closely as possible.

Some technical opportunities to alleviate the absence of natural light in underground spaces are met, simply by good architectural design, while the introduction of a somewhat more complex technology may be an effective measure. Other solutions can be:

- Large deep atrium spaces or courtyards that extend from the surface deep into the underground.
- The use of solar optics, which is the practice of projecting light into underground spaces by employing mirrors and optical lenses that track the sun and direct sunlight deep into the interior [17].
- Replicating the spectral compositions of daylight as closely as possible, using full-spectrum artificial light.
- The application of Virtual Natural Lighting Solutions (VNLS), which is a not-yet-existing system that artificially provides natural light and view with all of its qualities [18], [19].

7.1.2. *Indoor air quality*

The provision of fresh, clean air at comfortable temperature and humidity levels should not be more difficult underground than it is in conventional aboveground buildings. As there are some differences in the temperature and humidity conditions, the system has to be properly designed. The underground space users may be quite sensitive to ventilation, temperature and humidity problems. To offset negative reactions, strategies include the following [11]:

- Provide ventilation in a manner that is perceptible of the occupants.
- Provide a flexible mechanical system that can control both humidity and temperature to satisfy the function of each space as well as the comfort of the occupants.
- Proper use of air purification techniques to reduce the air pollution.

7.2. Appealing design techniques

In addition to providing a sufficient indoor environmental quality, entries, spaciousness and interior elements of underground buildings should be designed with particular sensitivity to offset the negative psychological effects.

7.1.3. *Sense of space and orientation*

Some applications of underground spaces provide minimal to no opportunities for exterior views. Small rooms and narrow corridors underground could contribute to many negative effects, such as claustrophobia, lack of orientation and lack of connection with the outside world. Techniques to alleviate this include the following [11]:

- Glass partitions between spaces as much as possible.
- Ceilings should be higher than dimensions in conventional buildings.
- The use of multi-level spaces to create spaciousness.
- Large deep atrium spaces or courtyards that extend from the surface deep into the underground.
- Make use of dissimilar columns (i.e. carved, designed, and marked in different ways) makes it possible for people to confirm the direction in which they are heading [16].
- Provide a variety of activities in the buildings and/or promote creative visual designs that will satisfy the need for visual variety.

7.1.4. *Interior design elements*

The sense of space created by high ceilings and glass partitions as well as the provisions of natural light proves the basic framework for the interior design elements. Certain elements generally contribute to creating a positive interior environment underground. These include [11]:

- The use of warm, bright colors, as opposed to dark colors or completely unfinished surfaces.
- Extensive use of green plants.
- Use of water in pools or fountain in appropriate locations.
- Variations in lighting in special areas, i.e. very bright light over a plant-filled area, or spotlight illuminating artwork.
- Artwork that serves as surrogate windows.

Table 4:** Comparison of different functions and how they affect benefits and drawbacks.

		BENEFITS					**DRAWBACKS**						
LEVEL OF REQUIREMENT*		🟩 MAJOR	🟢 MODERATE	🟦 NO			🟥 MAJOR	🔴 MODERATE	🟦 NO				
PRIMARY FUNCTION	**EXAMPLE OF USE**	Limited visual impact	Protection from noise and vibration	Provide security	Precise indoor climate control	Energy use reduction	Natural light and exterior view	Public visibility	Impact occupancy on internal gains	High ventilation rate	Lack of public acceptance	Large spans and height in spaces	Spatial orientation / Evacuation
Residential	Dwelling	🟦	🟩	🟢	🟢	🟩	🟥	🔴	🔴	🔴	🟥	🟦	🟥
	Hotel	🟦	🟩	🟢	🟢	🟩	🟥	🔴	🔴	🔴	🟥	🟦	🟥
Industrial	Manufacturing	🟢	🟩	🟢	🟦	🟢	🔴	🟦	🔴	🔴	🔴	🟥	🔴
	Laboratory	🟢	🟩	🟢	🟩	🟩	🔴	🟦	🔴	🔴	🟦	🟦	🔴
Commercial	Office	🟦	🟢	🟦	🟢	🟩	🟥	🔴	🔴	🔴	🟥	🟦	🟥
	Restaurant	🟦	🟢	🟦	🟢	🟩	🟦	🟥	🔴	🔴	🔴	🟦	🔴
	Shopping mall	🟩	🟢	🟦	🟢	🟩	🔴	🟥	🔴	🔴	🔴	🟥	🔴
Educational	Classroom	🟢	🟩	🟦	🟢	🟩	🟥	🔴	🔴	🔴	🟥	🟦	🔴
	Library	🟢	🟩	🟢	🟩	🟩	🟥	🔴	🔴	🔴	🔴	🟦	🟥
Medical	Hospital room	🟢	🟩	🟢	🟢	🟩	🔴	🔴	🔴	🔴	🔴	🟦	🟥
	Operating theatre	🟢	🟩	🟢	🟩	🟩	🔴	🟦	🔴	🔴	🔴	🟦	🟥
Religious	Religious building	🟦	🟢	🟦	🟢	🟢	🔴	🔴	🟥	🔴	🟥	🟥	🔴
Leisure	Swimming pool	🟦	🟢	🟦	🟢	🟢	🔴	🔴	🟥	🟥	🔴	🟥	🔴
	Theatre	🟦	🟩	🟦	🟢	🟢	🟦	🔴	🟥	🟥	🔴	🟥	🔴
	Cinema	🟢	🟩	🟦	🟢	🟢	🟦	🔴	🟥	🟥	🔴	🟥	🔴
	Disco	🟢	🟢	🟦	🟢	🟢	🟦	🔴	🟥	🟥	🔴	🟥	🟥
Storage	Wine cellar	🟩	🟦	🟢	🟩	🟢	🟦	🟦	🟦	🟦	🟦	🟦	🟦
	Bank vault	🟢	🟦	🟩	🟦	🟦	🟦	🟦	🔴	🔴	🟦	🟦	🟦
	Oil storage	🟩	🟦	🟢	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
Military	Fallout shelter	🟩	🟦	🟩	🟦	🟦	🟦	🟦	🔴	🔴	🟦	🟦	🟦
	Prison	🟩	🟢	🟩	🟩	🟩	🔴	🟦	🔴	🔴	🔴	🔴	🟥
Utility	Pedestrian transport	🟩	🟩	🟩	🟦	🟦	🔴	🟦	🟥	🟥	🟦	🟦	🟦
	Goods transport	🟩	🟩	🟩	🟦	🟦	🟦	🟦	🟦	🔴	🟦	🟦	🟦
	Waste water pipes	🟩	🟢	🟩	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
Agriculture	Mushroom growing	🟩	🟦	🟦	🟩	🟦	🔴	🟦	🟦	🔴	🟦	🟦	🟦
	Plant nursery	🟩	🟦	🟦	🟩	🟦	🔴	🟦	🟦	🔴	🟦	🟦	🟦

***Major** requirement in most or all cases / Only applies in some cases or to a **moderate** degree / **No** requirement.
**Rating primarily based on [3].

8. Climate

Although ground temperatures are often more favorable than the outside temperatures through the year, they can be less favorable at certain points in the seasonal cycle [3]. In a cold climate, the ground at a certain depth reaches its lowest temperature in spring. Although this time lag is beneficial in the summer, it is detrimental in the spring because the air temperatures, which are warming faster than the ground, would result in a lower heating requirement for the building if it were above grade. While in a warm climate, benefits from cooler fall air temperatures are greater than those from the ground, which has been warmed to its peak by the end of summer and early fall [3].

Different climates are therefore considered, as it directly influences a building’s design to cope with a certain climate. Three types will be discussed and associated climate data should be used for simulation purposes.

8.1. Hot-arid climate

In general, the hot-arid zone is where the greatest amount of solar radiation is encountered, perhaps the only regions where there is too much sun. This climate has a very high temperature in the daytime, and little or no precipitation. The climate is stressful with extremely high temperatures, dust-laden winds, and intense radiation together with ground reflection, all of which are detrimental to human comfort and health. These daily extremes of temperature can be destructive to building and building materials because of the daily expansion and contraction of the exposed surfaces, especially where there are different expansion rates [9].

For inhabitants of these areas, psychologically speaking the darker the room, the cooler it seems and minimal daylight seemed welcome by the population. Therefore, it is generally best to keep sunshine from entering the building in these regions [19].

The hot-arid climate is understandably the primary cause of large cooling energy consumption. However, the subsurface climate is much milder than the extremities of the aboveground environment. Being cooler than the ambient air for parts of the year, the soil enclosing an underground building has the potential to lessen the cooling energy needs of a building by reducing the heat transfer from its surrounding [9].

Ground temperatures in Kuwait are measured to be 24- 32˚C at a depth of 3m and 26- 29˚C at a depth of 6m [20].

8.2. Cold climate

Cold climates are characterized by long, usually very cold winters, and short, cool to mild summers. It offers extreme seasonal temperature variations where in winter, temperatures can drop to -40˚C and in summer, the temperature may exceed 30˚C. Because of consecutive months where the average temperature is below freezing, all moisture in the soil freezes solidly to a few meters into the ground.

As for the hot-arid climate, this climate is stressful with freezing temperatures through the year which is uncomfortable and requires high insulation values for conventional aboveground buildings to stabilize indoor temperatures.

The primary energy consumption is from heating. By enclosing the building with soil or building underground will reduce this consumption.

Ground temperatures in southern Finland are measured to be 3-8 ˚C at a depth of 3m and 5-6 ˚C at a depth of 7m [21].

8.3. Moderate climate

This climate generally features warm, but not hot summers and cool, but not cold winters, with a narrow annual temperature range. It typically lacks a dry season, as precipitation is more evenly dispersed through the year.

Ground temperatures in South West England are derived from the Labs [22] equation, which is a theoretical equation that estimates below ground temperatures for given surface temperatures and soil thermal properties. This gives temperatures of 8-17˚C at a depth of 3m and 12-14˚C at a depth of 7m [23].

9. Conclusion

Underground buildings help to reduce the energy consumption in comparison to a conventional above grade building by using beneficial soil temperatures and large amounts of earth cover as insulation. However some psychological and physiological effects discussed represent major drawbacks to a windowless, underground space.

It is difficult to assess all of the characteristics, because both the advantages and disadvantages are influenced by the function of the building and the underground building concept. Further, some of the important drawbacks, such as the absence of natural light and view induce a certain psychological unacceptability where the requirement varies per individual. Due to the lack of information on some of these topics it is impossible to draw definite conclusions. Many of these negative aspects can however be alleviated by measures involving appropriate designing to improve underground living.

The lack of available data on the energy performance of underground buildings, calls for a more detailed study, which includes different underground buildings concepts and evaluates their performance in several different climates.

This literature reviews provides a short overview of the available knowledge from previous studies involving underground building, and forms the basis of a subsequent study on the energy performance of underground buildings.

10. Works Cited

[1] L. Boyer, "Earth Sheltered Structures," *Energy,* vol. 7, pp. 201-219, 1982.

[2] E. von Meijenfeldt, Below Ground Level, Basel: Birkhauser - Publisher for Architects, 2003.

[3] J. Carmody and R. Sterling, Underground Building Design, Minnesota: Van Nostrand Reinhold Company Inc., 1983.

[4] M. Barker, "Using the Earth to Save Energy: Four Underground Buildings," *Tunneling and Underground Space Technology,* vol. 1, no. 1, pp. 59-65, 1986.

[5] A. El-Hamid and M. Khair-El-Din, "Earth Sheltered Housing: An Approach to Energy Conservation in Hot Arid Areas," *Architecture and Planning,* vol. 3, pp. 3-18, 1991.

[6] R. Sterling and J. Godard, "Geoengineering considerations in the optimum use of underground space," 2000.

[7] J. Godard, "Urban Underground Space and Benefits," in *World Tunnel Congress 2004 and 30th ITA General Assembly,* Singapore, 2004.

[8] T. Allison, "Building in the Kuwait Climate," Kuwait Insittue Scientific Research, 1975.

[9] A. Al-Temeemi and D. Harris, "A guideline for assessing the suitability of earth-sheltered mass-housing in hot-arid climates," *Energy and Buildings,* vol. 36, pp. 251-260, 2004.

[10] F. Chow, T. Paul, I. Vähäaho, B. Sellberg and L. Lemos, "Hidden Aspects of Urban Planning: Utilisation of Underground Space," Zurich, 2002.

[11] J. Carmody and R. Sterling, "Design Strategies to Alleviate Negative Psychological and Physiological Effects in Underground Space," *Earth Shelter & Architecture,* vol. 2, no. 1, pp. 59-67, 1987.

[12] G. Golany, Earth-sheltered Habitat, New York: Van Nostrand Reinhold, 1983.

[13] M. Jannadi and S. Ghazi, "Earth-sheltered housing: the way of the future," *Journal of Urban Planning and Development,* vol. 124, no. 3, pp. 101-115, 1998.

[14] R. Behr, "Suitable thin shell structural configuration for earth sheltered housing," Texas Tech University, Texas, 1982.

[15] J. Carmody and R. Sterling, Underground space designs, A guide to Subsurface Utilization and Design for People in Underground Spaces, Van Nostrand Reinhold, 1993.

[16] H. Xueyuan and S. Yu, "The Urban Underground Space Environment and Human Performance," *Earth Shelter & Architecture,* vol. 3, no. 2, pp. 193-200, 1988.

[17] H. Parker, "Underground Space: Good for Sustainable Development, and Vice Versa," Singapore, 2004.

[18] R. Mangkuto, M. Aries, E. van Loenen and J. Hensen, "Lighting performance of virtual natural lighting solutions with a simplified image in a reference office space," in *Proceedings of Experiencing Light 2012*, Eindhoven, the Netherlands, 2012.

[19] R. Mangkuto, M. Aries, E. v. Loenen and J. Hensen, "Properties of Performance Indicators of Virtual Natural Lighting Solutions," in *Proceedings of CISBAT, Lausanne, September 2011*, Lausanne, Switzerland, 2011.

[20] J. Reynolds, "Passive cooling and courtyards in Colima, Mexico," *Passive and Low Energy Alternatives,* vol. 1, no. 13, pp. 15-22, 1994.

[21] A. Al-Temeemi and D. Harris, "The effect of earth-contact on heat transfer through a wall in Kuwait," *Energy and Building,* vol. 35, pp. 399-404, 2003.

[22] R. Lemmelä, Y. Sucksdorff and K. Gilman, "Annual variation of soil temperature at depths 20 to 700 cm in an experimental field in Hyrylä, South Finland during 1969 to 1973," Helsinki, 1973.

[23] K. Labs, "Underground Building Climate," *Solar Age,* vol. 4, no. 10, 1979.

[24] D. Harris, "Ground temperatures in Britain," *International Journal of Ambient Energy,* vol. 27, no. 3, pp. 149-159, 2006.

II. Underground buildings
Potential in terms of energy reduction

Underground buildings
Potential in terms of energy reduction

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ABSTRACT: Underground buildings are pointed out as an alternative to conventional aboveground buildings for reducing the total energy requirements, while alleviating land use and location problems. This paper investigates the potential in reducing the energy demand of underground buildings compared to aboveground buildings. Monthly calculations based on EN-ISO 13790 are performed to obtain the annual energy demand of an aboveground building and underground building. By comparing the annual energy demands for different climates, building functions and underground depths, deductions can be made to quantify the energy reduction potential of underground buildings. Introducing variable input parameters allows identification of the influence of design options on the annual energy demand of a building. Results identify that a variety of the underground building cases can almost be considered to be zero-energy buildings (annual energy demand below 10 kWh/m^{2}a). In contrast to the aboveground counterpart where the energy demand is up to 100 kWh/m^{2}a higher. The low annual energy demand for these underground building cases originates from the balancing energy flows. The transmission losses of the underground building are at a stable value annually in comparison to the aboveground situation, where it varies with seasonal weather changes. Underground buildings can help to reduce the energy demand in comparison to a conventional aboveground building by using beneficial soil temperatures and large amounts of earth cover as insulation. Energy reduction is achievable for all climates and functions, but the magnitude is related to the combination of different design elements. Sensitivity analysis shows that building functions with high internal gains induce an inefficient balance in tropical to warm climates for underground buildings, but strongly reduce the heating demand in cold climates. Furthermore, ground properties have a small influence on the energy demand of an underground building.

KEYWORDS: underground buildings, energy balance, energy conservation, Monte Carlo analysis, sensitivity analysis.

1. INTRODUCTION

Pressing problems that mankind is currently faced with, are the energy crisis and increasing demand for buildings caused by the continuous growth in the world's population [1] [2] [3] [4]. Solutions such as building underground are pointed out as an alternative to conventional aboveground buildings for reducing the total energy requirements, while alleviating land use and location problems [5] [6] [7] [8]. Although research is done on various aspects of underground building heat transfer [2], [9], [10], no study has been found that investigates the relationship between different design elements of an underground building and its regional climate, which determine its energy performance. A comparative analysis is needed to quantify the difference in the annual energy demand between an aboveground building and underground building [11]. This study incorporates such an analysis by including different climates, functions and depths to assess the energy reduction potential of underground buildings. By applying variable input parameters the influence of design options on the annual energy demand of a building can be investigated.

This paper presents results of a comparative study on the annual energy demand of an underground- and aboveground building. The scope of the study includes 15 different climates, 6 building functions and 3 underground depths and the annual energy demand is calculated using 11 variable building input parameters.

2. METHODOLOGY

The building's energy need for space heating and -cooling is calculated using the monthly method described in EN-ISO 13790 [12]. The procedure for the investigation is visualized and described in a flowchart (**Figure 1**) and follows three steps; pre-processing, calculation and post-processing. In the pre-processing stage, the building functions, weather data and variable input parameters are defined. The variable input parameters are obtained from literature and are processed into samples using Latin hypercube sampling (LHS). In the calculation stage, the annual energy demand for the aboveground- and underground building is calculated with 200 different combinations of input variables. This is done for 15 different climates, 6 building functions and 3 depths, which totals to 540 different cases. In the post-processing stage, the annual energy demand and influence of the variable input parameters are analyzed using uncertainty and sensitivity analysis.

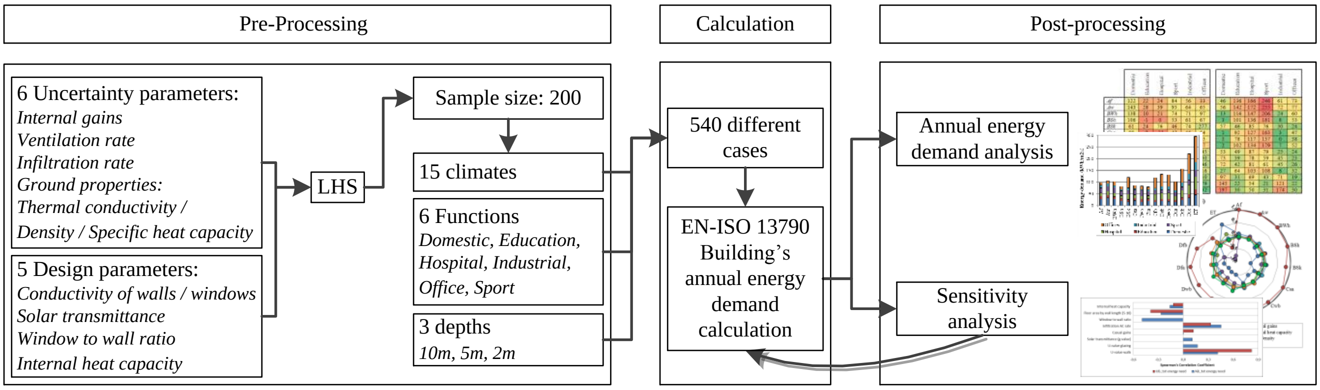
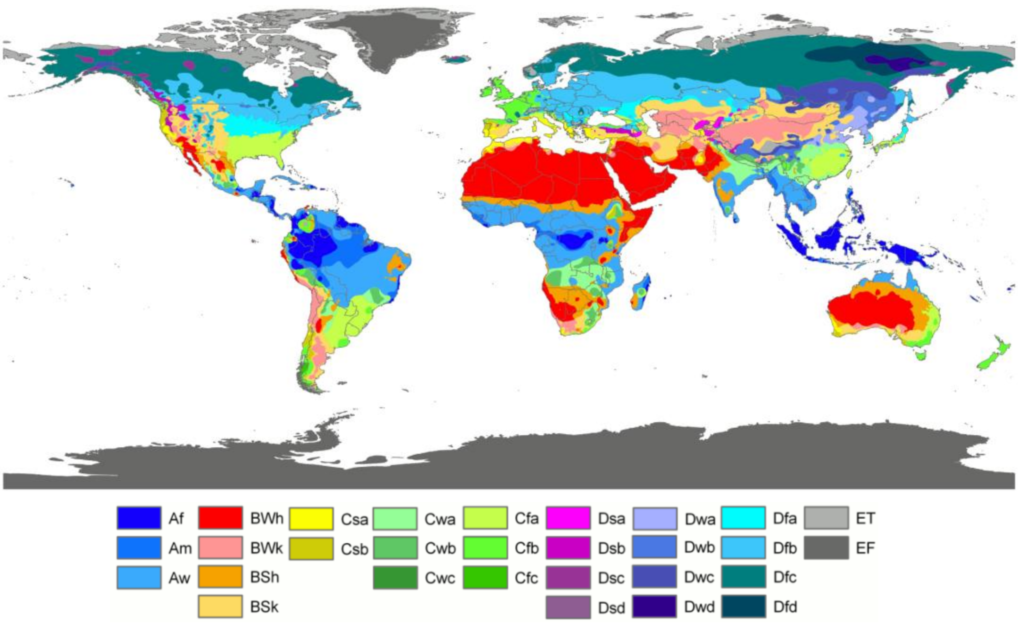


Figure 1: Flowchart of the investigation procedure.

2.1. Climate- and building specifications

The Köppen-Geiger climate classification is used to differentiate climates [13]. Weather data for each climate is obtained using TMY2 data for a city located in a corresponding climate. Although the main weather characteristics are maintained between different locations in the same climate, certain deviation exists between the raw values. In total 15 of the 30 climates are chosen with a corresponding location on earth (**Figure 2**). Only 15 have been chosen due to the large amount of data acquired with calculating every climate. For every climate group (A to E) at least one climate is chosen. Climate descriptions are shown in **Table A. 1** in **Appendix A**.



Af	Singapore
Aw	Bangkok
BWh	Phoenix
BSh	San Antonio
BSk	Colorado Springs
Csa	Seville
Cwb	Johannesburg
Cfa	Jacksonville
Cfb	Amsterdam
Dsb	Great Falls
Dwb	Minneapolis
Dfa	Kansas City
Dfb	Helsinki
Dfc	Sodankylae
ET	Inukjuak

Figure 2: Köppen-Geiger climate classification map of the world [13], with the chosen climates and corresponding cities.

The annual energy demand is examined for 6 different building functions (**Table 1**). Building characteristics for different functions are obtained from the U.S. building stock [14].

Table 1: Building characteristics for different building functions

	Domestic	Education	Hospital	Industrial	Offices	Sport	
Occupancy density [m^2/pp]	60	10	30	20	20	20	[12]
Floor area [m^2]	120	19592	22422	5000	46320	1500	[14]
Number of floors	3	2	5	1	12	1	[14]
Height per floor [m]	2.8	4	4.3	8.5	4	7.6	[14]
Aspect ratio [EW / NS]	1.2	1.3	1.3	2.2	1.5	1.2	[14]

Dimensions for the domestic building function are assumed.
Education is based on the size of a secondary school, industrial on a warehouse and offices on a large office.
Sport building function is based on a 33m x 18m x 7.6m four-court hall, with attachments.

The variable input parameters evaluated in this study can be divided into uncertainty- and design parameters. The uncertainty parameters internal gains and ventilation rate are normally distributed around a mean with a standard deviation (**Table 2**). The uncertainty parameters infiltration rate, ground properties and design parameters are uniformly distributed to represent a range of possible values (**Table 3**). The range of occurrence is determined by the use of published data or follows from assumed values. The value of the uncertainty variables and design variable infiltration rate are dependent on the size of the building and occupancy density. Therefore the size and accordingly the level of impact of these variables are considered during the evaluation of the results. The variable input parameters are different for the aboveground- and underground building. For the underground building it is assumed that there are no windows nor is there any infiltration. Calculations for the aboveground building do not take into account the changing ground properties. A total of 8 input parameters are therefore used for the annual energy demand calculations of the aboveground building and 9 for the underground building.

Table 2: Normally distributed uncertainty variables

		Domestic	Industrial	Education	Hospital	Offices	Sport	
Internal gains[1] [W/m^2]	μ	4.6	6.42	15.25	18.66	8.17	27.25	[12], [15]
	σ	0.575	1.906	2.332	0.802	1.021	3.406	(25%)
Ventilation rate[2] [m^3/h.pp]	μ	42	14	7	30	14	14	[12], [15]
	σ	5.250	0.875	3.750	1.750	1.750	1.750	(25%)

Uncertainty variable distribution: Both uncertainty variables are normally distributed.

[1] Gains are dependent of floor area. Internal gains include the combination of metabolic (people), lighting and appliance gains multiplied by the fraction of time present, which depends on the building function.

[2] The total ventilation requirement depends on the occupancy density and floor area of the building.

Table 3: Uniformly distributed variables

		Minimum	Maximum	
Design variable	Conductivity of walls[1] [W/m^{2}K]	0.1	0.3	Assumption
	Conductivity of windows [W/m^{2}K]	0.5	1.5	Assumption
	Solar transmittance (g-value)	0.3	0.7	Assumption
	Window to wall ratio	0.3	0.8	Assumption
	Internal heat capacity[2]	80,000	370,000	[12]
Uncertainty variable	Infiltration rate[3] [1/h]	0.15	0.25	[15]
	GP[4]: Thermal conductivity [W/mK]	0.9	3	[16]
	GP[4]: Density [kg/m^3]	1500	2700	[16]
	GP[4]: Specific heat capacity [J/kgK]	700	2200	[16]

Uncertainty and design variable distribution: All variables are uniformly distributed.

[1] The U-value of walls excludes the surface heat transfer coefficients, which are included in the calculation.

[2] 80,000 corresponds to a very light building and 370,000 to a very heavy building.

[3] The range for the infiltration rate corresponds to a tight to very tight building.

[4] GP stands for ground properties and includes variations of clay and sand soils.

2.2. Analysis and sampling techniques

A sample matrix for the input parameters is created by using Latin hypercube sampling (LHS). LHS has the advantage that large amounts of input variable parameters can be presented by small sample sizes [10]. The minimum number of samples depends on the number of variables and is determined by the accuracy of the standard deviation in the annual energy demand. A sufficient accuracy can be achieved with 200 iterations. To analyze the approximate distribution of possible results on the basis of variable input parameters, the global analysis method Monte Carlo analysis is applied [17] [18]. It requires the sampling of multiple input parameters. All variable inputs are assigned a probability distribution and are varied simultaneously to consider the sensitivity due to the uncertainties in the input [17]. Subsequently uncertainty analysis obtains the variability in the annual energy demand. And sensitivity analysis identifies the influence of variable input parameters on the annual energy demand.

2.3. Energy calculation (EN-ISO 13790)

Calculations are made for a single-zone building being fully underground, therefore the assumption is made that no infiltration or solar gains are existent. The building's need for space heating and space cooling is calculated using the monthly method described in EN-ISO 13790 [12]. In principle there is an energy need when the zone needs heating to raise the internal temperature to the required minimum level (set-point for heating) or when the zone needs cooling to lower the internal temperature to the required maximum level (set-point for cooling). The total heat gains (internal- and solar gains) and heat losses (transmission- and ventilation losses) are calculated for the heating and cooling mode with a corresponding utilization factor. The utilization factor is a function of the heat balance ratio for both heating and cooling and requires a numerical parameter that depends on the building's thermal inertia [12]. The appropriate temperature difference compared to heat transmission to the external environment, due to the large inertia of the ground, is taken into account by an adjustment factor that adjusts the heat transfer coefficient instead of the temperature difference. The transmission losses to the ground are calculated by using this factor in combination with calculated ground temperatures.

No energy consumption is calculated for lighting in an underground building compared to an aboveground building as the method does not take into account energy required for the system's electricity use. This also means that there is no difference between the use of natural- and mechanical ventilation. In case a difference could be made, it should be noted that many aboveground buildings do not use daylight or natural ventilation efficiently. Thus no advantage is taken of these passive energy flows compared to underground buildings.
The aboveground building does not take into account any shading devices, as alternative measure the solar heat gain coefficient (g-value) of the window ranges to a low value 0.3, which corresponds to a window that only transmits a small amount of solar heat.

2.4. Ground temperatures

Ground temperatures are calculated using an analytical equation developed by Labs [19] that predicts the long-term annual pattern of soil temperature variations as a function of depth and time for different soils and soil properties. The average monthly surface ground temperature is assumed to be equal to the monthly air temperature, which is the starting point of several building energy simulation programs [20].

The equation is as follows [19]:

$$T_{(x,t)}=T_m-A_s e^{-x\sqrt{\frac{\pi}{365\alpha}}} \cos\left\{\frac{2\pi}{365}\left[t-t_0-\left(\frac{x}{2}\right)\left(\sqrt{\frac{365}{\pi\alpha}}\right)\right]\right\}$$

Where:

$T_{(x,t)}$ = temperature of soil at depth x and on day t of the year in ˚C

T_m = mean annual ground surface temperature ˚C

x = depth below surface in m

t = time of year in days (Jan 1 = 1)

t_0 = the phase constant, corresponding to the day of minimum surface temperature (days)

α = the thermal diffusivity of the soil (m^2/day)

As = amplitude of surface temperature wave

The cosine is expressed in radians.

This analytical equation does not take into account the precipitation and ground properties for every unique spot, which are dissimilar at different locations and depths. The thermal diffusivity of the soil is based on its density, thermal conductivity and specific heat capacity. The thermal diffusivity depends on the type of soil and because this differs per location, it has been chosen to make the ground properties variable to include the range of probable soil types.

The ground temperature is calculated for 15 climates with different ground properties. The ground temperature profiles have a sinusoidal diurnal pattern, which follow the same pattern as the air temperature. Larger amplitudes between the different depths exist in climates where the seasonal temperature difference is larger. In the tropical climates (Af, Aw), the annual temperature can have a variation of only a few degrees Celsius, therefore also the ground temperatures have a small fluctuation throughout the year. For the BSh, Cfb and Dfb climates the amplitudes are larger than those of the tropical climates. The sinusoidal pattern of the temperature dampens with an increase of depth. For the calculation of the energy demand of the underground building, three depths (2m, 5m and 10m) have been chosen with their corresponding ground temperatures. Underground temperatures at a depth of 2m have a larger fluctuation than at a depth of 10m, which is almost stable, but still fluctuates less than the outdoor temperature.

2.5. Post-processing annual energy demand

For each case, with altering climate, function and depth, 200 calculations provide 200 different values for the annual energy demand for both the aboveground building and underground building. Due to the variability of the input, a standard deviation exists in the annual energy demand. This makes it possible to analyze and show the frequency distribution of the annual energy demand per case. But due to the large amount of cases, these plots do not give a good overview of the results. Therefore comparison will be done on the mean and standard deviation of the 200 resulting outputs per case.

Spearman’s rank correlation [21] is applied to identify whether the input variables and annual energy demand relate in a monotonic function, meaning that if an input variable increases or decreases, the annual energy demand increases or decreases. Spearman’s rank correlation coefficient is a non-parametric measure of correlation as it does not try to make any assumption about the nature of the relationship between two ranks.

3. RESULTS AND DISCUSSION

Results are presented by showing the absolute values and value differences of the annual energy demand for the aboveground building and underground building for different climates and functions. Total uncertainties are defined by the standard deviation. And the sensitivity of the input variables on the output is shown using Spearman’s rank correlation.

3.1. Annual energy demand comparison

A first analysis of the results shows that the differences in annual energy demand between the underground depths are relatively small and that for most cases an underground depth of 10m performs best. Therefore comparisons will be made between the aboveground building and an underground building which is calculated using temperatures at a depth of 10m.

Due to the large amount of different cases the mean values of the annual energy demand (kWh/m^{2}a) are compared by subtracting the total annual energy demand of the aboveground building with those of the underground building (**Table 5**). Summing the values from both tables shows the annual energy demands of the aboveground building (AB) (= **Table 4** + **Table 5** or AB = (AB-UB)+UB)). This gives the possibility to quickly see potential sources of energy reduction by using colors, and it shows the climates and functions that have a low annual energy demand in **Table 5** (green to red – small to large energy demand). In **Table 4** a larger difference induces a higher energy reduction, as is indicated by the colors (green to red – large to small difference). A negative value indicates that the aboveground situation performs better than the underground situation and is therefore colored red. A comparison to the actual values is necessary to show the relevance of the energy reduction.

Table 4: Difference between mean annual energy demand (kWh/m^{2}a) of the **aboveground building and underground building** for different climates and building functions.

		Domestic	Education	Hospital	Sport	Industrial	Offices
Singapore	*Af*	122	22	24	84	56	33
Bangkok	*Aw*	143	28	39	95	64	65
Phoenix	*BWh*	138	10	21	74	71	97
San Antonio	*BSh*	106	-1	0	53	61	67
Colorado Springs	*BSk*	61	24	76	46	74	277
Seville	*Csa*	88	-9	-11	42	46	64
Johannesburg	*Cwb*	33	-21	-31	27	15	65
Jacksonville	*Cfa*	95	-4	-9	49	52	47
Amsterdam	*Cfb*	53	-2	43	14	53	245
Great Falls	*Dsb*	80	41	104	69	81	330
Minneapolis	*Dwb*	97	55	118	95	99	346
Kansas City	*Dfa*	107	22	58	58	96	216
Helsinki	*Dfb*	92	48	132	71	81	410
Sodankylae	*Dfc*	123	92	223	124	107	579
Inukjuak	*ET*	143	127	314	150	134	732

green to red
large to small **difference** in energy demand

Table 5: Mean annual energy demand (kWh/m^{2}a) of the **underground building** for different climates and building functions.

		Domestic	Education	Hospital	Sport	Industrial	Offices
Singapore	*Af*	46	136	166	246	61	73
Bangkok	*Aw*	56	142	172	255	72	77
Phoenix	*BWh*	13	116	147	206	24	60
San Antonio	*BSh*	3	101	136	181	8	53
Colorado Springs	*BSk*	57	46	85	76	30	24
Seville	*Csa*	1	92	127	163	3	47
Johannesburg	*Cwb*	5	78	117	137	0	38
Jacksonville	*Cfa*	2	102	134	179	7	52
Amsterdam	*Cfb*	53	49	87	79	25	24
Great Falls	*Dsb*	73	39	78	59	45	23
Minneapolis	*Dwb*	72	42	81	61	45	26
Kansas City	*Dfa*	27	64	103	108	8	32
Helsinki	*Dfb*	97	31	69	43	71	19
Sodankylae	*Dfc*	145	22	54	21	121	22
Inukjuak	*ET*	197	30	50	31	174	30

green to red
small to large energy demand

Results show that a variety of the underground building cases can almost be considered zero-energy buildings as the annual energy demand is near zero (below 10 kWh/m^{2}a), in contrast to the aboveground counterpart where the energy demand is up to 100 kWh/m^{2}a higher (**Table 4**). The low annual energy demand for these underground building cases, which can be seen in a large range of climates, originates from balancing energy flows. Due to the building being underground, the transmission losses are stable throughout the year in comparison to the aboveground situation, where it varies due to the seasonal weather changes.

Table 4 and **Table 5** also show that there can be a large difference between the aboveground- and underground buildings for different functions in the same climate. This difference is largely dependent on the size of the building in combination with the internal gains. Building functions with low internal gains have a higher energy demand in colder climates, while building functions with high internal gains have a high energy demand in warm climates and vice versa. Warm to temperate climates (Af to BSh and Csa to Cfb) show a low energy reduction (up to 30%) for the education, hospital and sport building functions, and in some cases are even less efficient (down to -30%) than its aboveground counterpart.

3.2. High potential case

An example of balancing energy flows is given subsequently for a specific climate (Cfa) and building function (domestic). **Figure 3** shows that the underground building (*right graph*) has an underground temperature (UB temperature) at the lower level of the set-point temperature interval. The balance of the energy losses and gains will decide whether a comfortable temperature can be maintained without any requirements for heating or cooling. On the other hand an aboveground building (*left graph*) has fluctuating annual outside temperatures (AB temperature). This causes the temperature to be inside the interval for several months (April, May and September), but to be outside the interval for the remaining months. Furthermore, the transmission and ventilation losses are higher in the winter resulting in a larger energy need for heating. In contrast to underground buildings, aboveground buildings can make use of solar gains. The annual energy demand difference between the aboveground building and underground building for this specific climate and function is 88 kWh/m^{2}a. However, for the same climate, a hospital building function with higher internal gains causes overheating in the underground building and subsequently requires more energy for cooling, this result is also visible in **Table 5**. In the Cfa climate, a domestic underground building function is much more energy efficient than the aboveground building, but for a hospital building function it performs worse by a margin of 9 kWh/m^{2}a.

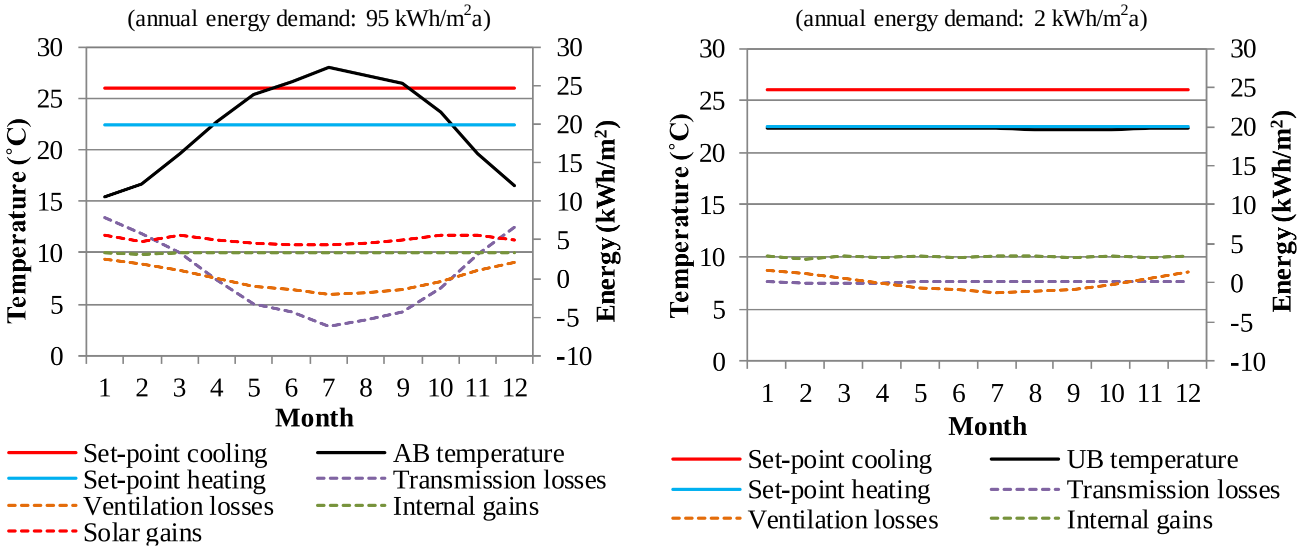


Figure 3: Energy balance of an **aboveground** building (**left**) and **underground** building (**right**) show the cause of the difference in annual energy demand, for the Cfa climate and a domestic building function.

3.3. Energy loss due to infiltration

In **Table 5** high values of energy reduction can be seen for the office building function in the colder climates (BSk, Cfb to ET) and for the very cold climates (ET and Dfc). The large difference is solely caused by the infiltration rate (1/h) of the aboveground building (**Figure 4**, *left graph*), where a comparison is made between different values of the infiltration rate for an office building in the ET climate. The annual energy demand of the aboveground building without infiltration is 56 kWh/m^{2}a (for comparison the energy demand of the underground building (*right graph*) is 42 kWh/m^{2}a). A drastic increase of the ventilation losses due to the increase of the infiltration rate is visible (infiltration rate (1/h) = 0.1, 0.15, 0.2 corresponds to an annual energy demand of 406, 590, 775 kWh/m^{2}a respectively. Ventilation losses are named infiltration = “value” in the graph, as infiltration is considered to be part of the ventilation losses)). The effect is significant for the colder climates, as cold outside air seeps into the building and subsequently, the building requires more energy for heating. An explanation for this is that the infiltration rate (1/h) depends on the volume of the building and the annual energy demand (kWh/m^{2}a) is calculated for the floor area of the building. This means that the building functions with a high volume to floor area ratio (offices and hospital) have a proportionally larger infiltration and therefore require more energy in the colder climates.

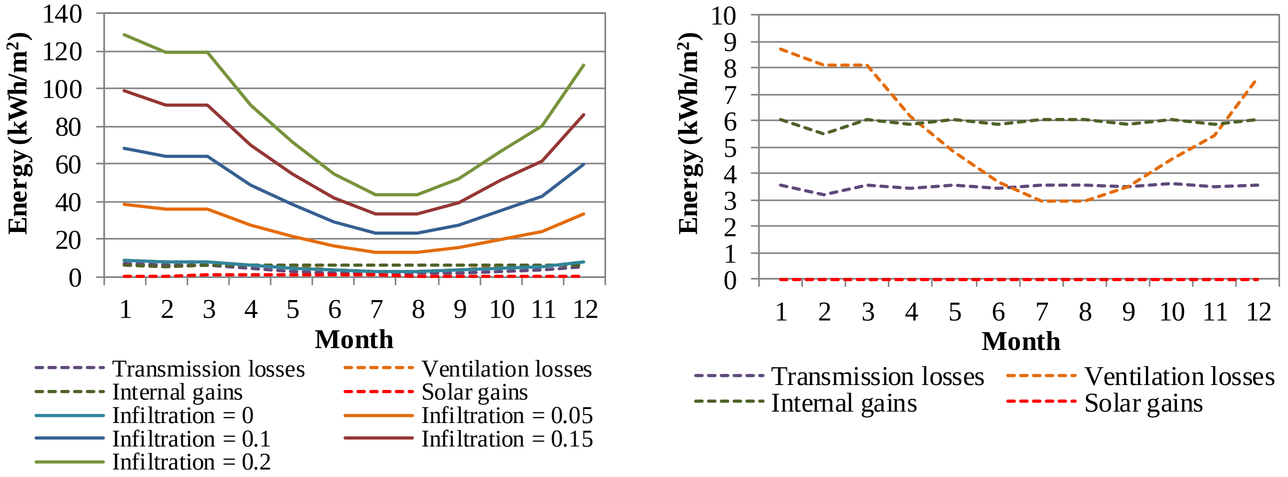


Figure 4: Energy balance of an **aboveground** building (**left**) and **underground** building (**right**) in the ET climate for the office building function.

3.4. Rationale of the energy balance of a building

Understanding the energy balance of a building is very important to comprehend the results and their relationship between different combinations of climates and functions. The rationale for the energy balance is that the annual energy need of a building depends on the deviation from the interval between the heating and cooling set-point temperatures. As derived from the presented results, there are some underground building cases that show an almost zero-energy demand. The prime reason for this is that the underground temperature maintains a stable value inside the set-point interval throughout the year. This signifies that no energy is required to maintain the internal temperature at a comfortable level, unless the internal gains cause an imbalance. Therefore the underground temperature is very important to achieve a high energy reduction. In contrast, the aboveground building is exposed to outside temperatures with larger daily and seasonal temperature fluctuations that deviate from the interval and require more energy to maintain a comfortable internal temperature. Furthermore, certain climates have underground temperatures that are below the heating set-point. Depending on the range of this deviation, extra energy for heating is required to maintain the comfortable internal temperature. In these cases it can be advantageous to have a building function with high internal gains that nullify large amounts of transmission losses to balance the equation. In warm climates (high underground temperatures) internal gains are therefore superfluous and would only increase the cooling demand. In contrast to cold climates, internal gains are useful to reduce the heating demand. A sports building function (high internal gains) is therefore inefficient in a warm climate, but efficient in a cold climate, but for a domestic building function (low internal gains) the situation is reversed. These results are calculated without using hourly user schedules (such as for the temperature set-points and occupancy pattern) throughout the day. This may cause a day and night time fluctuation that could influence the energy demand for a building in certain climates.

3.5. Uncertainty analysis

The distribution of the annual energy demand per case can be shown by using a frequency distribution (**Figure 5**). In this particular case, the annual energy demand of the underground building has a much lower mean than the aboveground building, but also shows that its standard deviation is much smaller.

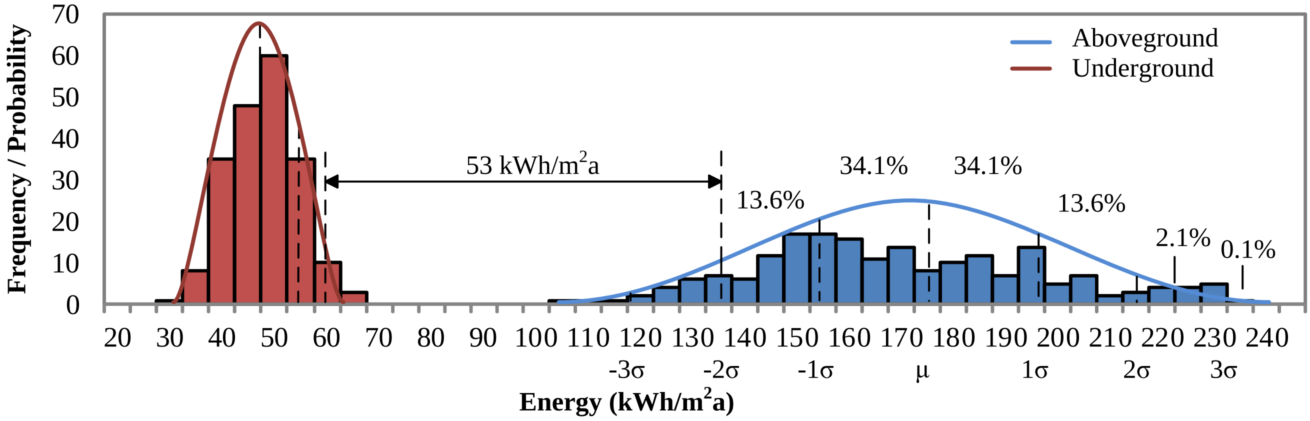


Figure 5: Frequency distribution and probability distribution of the annual energy demand for the **Af** climate and **domestic** building function, for 200 different combinations of variable input parameters.

An important observation is made when comparing the best case (lowest energy demand) of the aboveground building with the worst case (highest energy demand) of the underground building. The mean and standard deviation values of the annual energy demand for the aboveground- (AB) and underground (UB) buildings in the previous example are, AB (μ = 167 σ = 28) and UB (μ = 46 σ = 7). The best aboveground building is then 167-28 = 139 kWh/m^{2}a, while the worst underground building is 46+7 = 53 kWh/m^{2}a, this differs by 139-53 = 86 kWh/m^{2}a. For 2 standard deviations, there is therefore a ~95% (0.976^2) chance that the difference in the annual energy demands of the aboveground- and underground building is 53 kWh/m^{2}a or more. The best aboveground building case will thus perform worse than the worst underground building case by a large margin.

The same comparison is made for every climate and building function. In most cases the worst underground building performs better than the best aboveground building (positive interval value). Except for the Af to Cfb and Dfa climates for the education, hospital and sport building functions. In these cases the 2 standard deviation interval value between the worst and best case is negative. In some of these cases this already follows from the negative difference in the mean and almost equal standard deviation.

3.6. Sensitivity analysis

By analyzing the influence of design and uncertainty parameters on the annual energy demand, strong correlations can be identified. This can be helpful to determine which level of design is required to attain the highest performance.

Figure 6 shows Spearman's rank correlation coefficients for the sport building function in a tropical (Af) and polar climate (ET). It can be seen that in the tropical climate, the internal gains indicate a very strong positive correlation to the annual energy demand of an aboveground- and underground building. In the polar climate on the other hand, the internal gains correspond to a negative correlation for both an aboveground- and underground building.

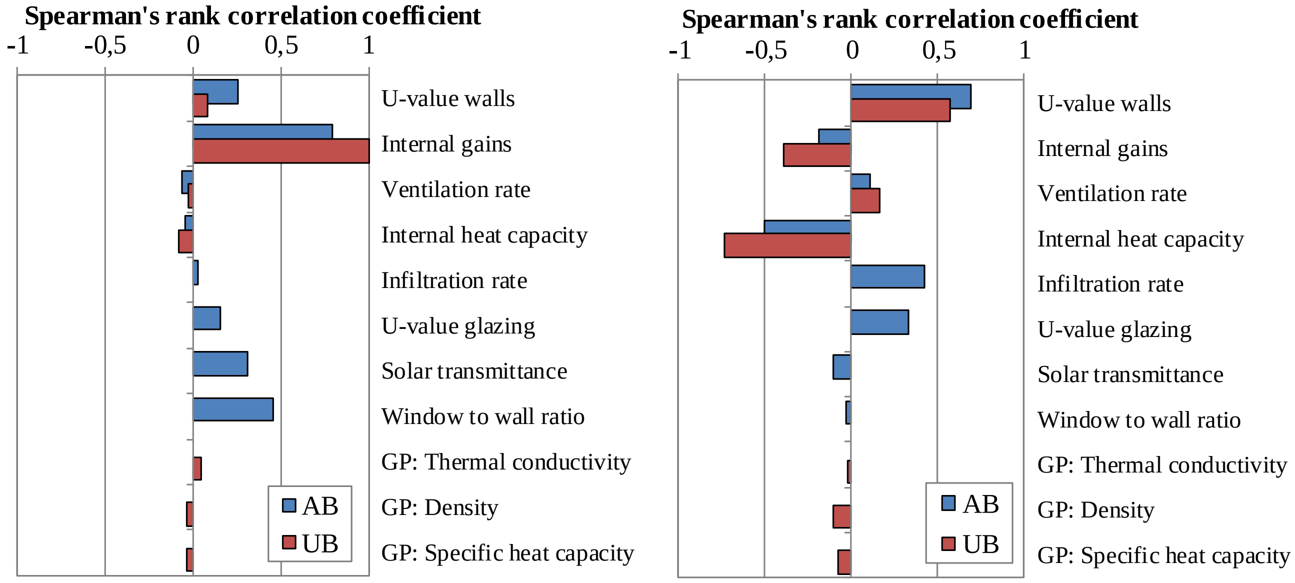
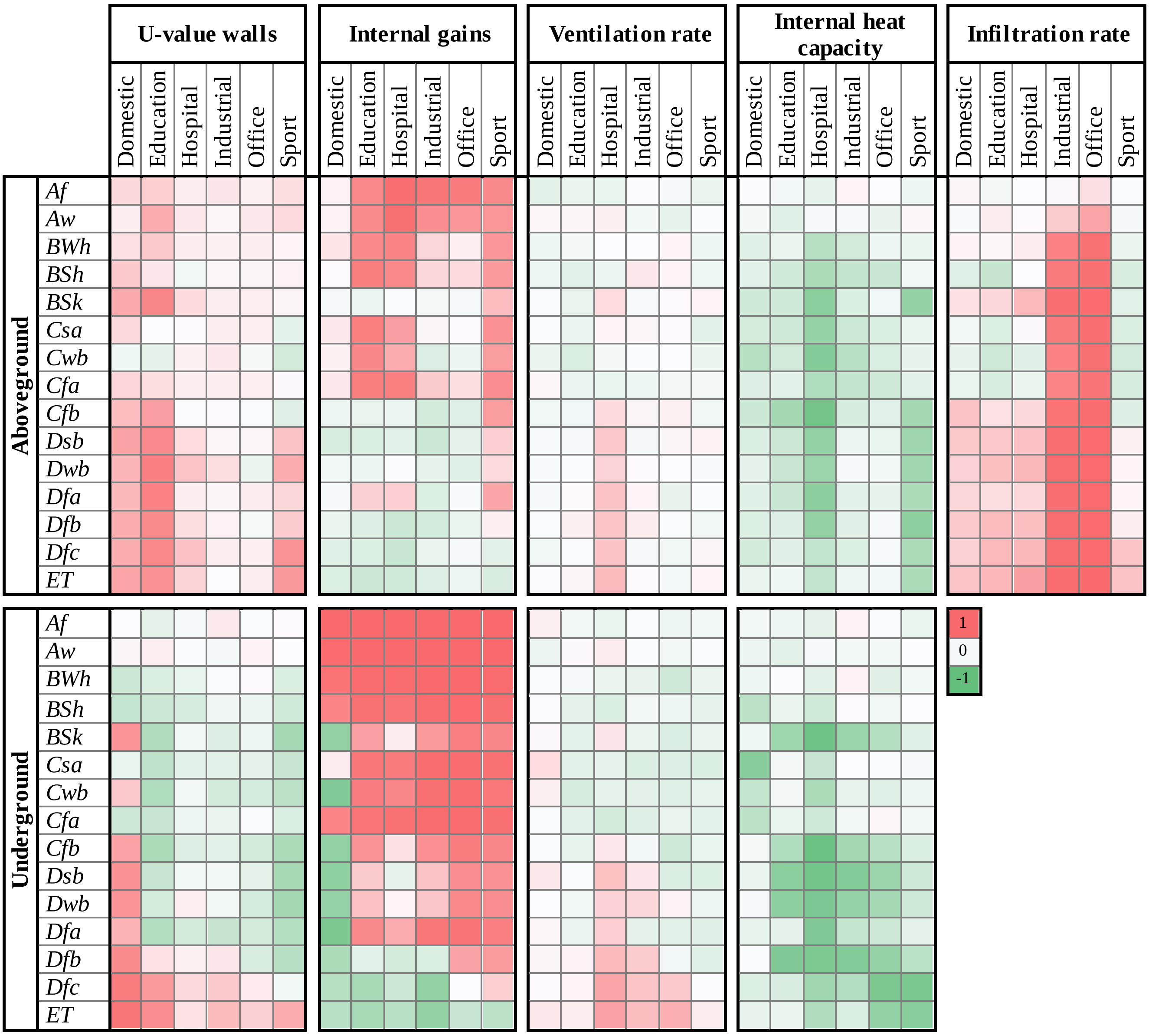


Figure 6: Spearman's correlation coefficient on the annual energy demand of an aboveground- (AB) and underground building (UB) with sport function, for the tropcial climate **Af** (**left**) and polar climate **ET** (**right**).

The correlation coefficients of the 5 most important variable parameters on the annual energy demand for an underground- and aboveground building for all building functions and climates are shown in **Table 6**. The correlation is visualized by using a color scale, -1 very strong negative correlation (red) to 1 very strong positive correlation (green), 0 (white) means there is no correlation.

No single parameter seems to have the highest influence in every situation, although there are some parameters that have a higher influence in most cases. The ground property parameters are not shown for the underground building as their influence on the annual energy demand is very small, which is also observed in a former study [22]. Furthermore, 3 parameters for the aboveground building are not shown as they only have a strong influence for the domestic building function. The U-value of the windows has a strong negative influence in the colder climates, while solar transmittance and window to wall ratio have a strong negative influence in the warmer climates.

Table 6: Variable parameter analysis on annual energy demand (negative (-1 "green") to positive (1 "red") correlation).



The annual energy demand is strongly influenced by several parameters, and there exists a large difference in correlation between the climates and building functions.

- An increase in the U-value (lower resistance) will almost always increase the energy demand of an aboveground building, stronger so in the colder climates. On the contrary, the energy demand of an aboveground building in the warm climates increases when the U-value is decreased (higher resistance).
- Higher internal gains increase the energy demand in warm climates and reduce the energy demand in cold climates for both the aboveground- and underground building. But for the underground building, the parameter is much more sensitive and has a larger negative effect in most of the climates. It is the most important parameter for the underground building.
- A decrease in the internal heat capacity of a building has a positive influence on the energy demand in almost all cases.
- For larger aboveground buildings the infiltration rate has a strong negative correlation with the energy demand, for the remainder of the buildings, the correlation is also existent in the colder climates. Much energy is saved in the underground building due to the absence of this unwanted air infiltration.

From the sensitivity analysis it follows that the combination of parameters in a certain climate and building function can have a large influence on the energy demand of both an underground and aboveground building. Thus to achieve the highest possible energy reduction through optimization, a dissimilar combination of parameters is required for every different climate and building function.

4. CONCLUSION

The energy reduction potential of underground buildings has been investigated by performing monthly calculations on the annual energy demand. A comparative analysis between aboveground- and underground buildings is applied for different climates, building functions and depths. This made it possible to quantify the differences and assess the energy reduction potential. A sensitivity analysis is performed by analyzing variable input parameters and their correlation on the annual energy demand.

Underground buildings have the potential to reduce the energy demand in comparison to a conventional aboveground building by using beneficial soil temperatures and large amounts of earth cover as insulation. But the magnitude of this potential is related to the combination of different design elements. The energy reduction potential starts with underground buildings that require almost no energy to maintain a comfortable indoor temperature, as can be seen in several climates. The prime reason for this is that the underground temperature maintains a stable value inside the set-point interval throughout the year. This signifies that no energy is required to maintain the internal temperature at a comfortable level, unless the certain parameters, such as the internal gains cause an imbalance. Therefore the underground temperature is very important to achieve a high energy reduction. In contrast, the aboveground building is exposed to outside temperatures with larger daily and seasonal temperature fluctuations that deviate from the interval and require more energy to maintain a comfortable internal temperature. According to the calculation of different ground depths (2m, 5m and 10m), it is concluded that their mutual effect on the annual energy demand of an underground building is negligible. Furthermore, variable ground properties show only a very small influence on the energy demand of an underground building.
Certain climates have underground temperatures that are below the heating set-point. Depending on the range of this deviation extra energy for heating is required to maintain a comfortable indoor temperature. In these cases it can be advantageous to have a building function with high internal gains that nullify large amounts of transmission losses to balance the equation. In warm climates (high underground temperatures) internal gains are therefore superfluous and would only increase the cooling demand. In contrast to cold climates, internal gains are useful to reduce the heating demand.
A high energy demand is perceived for large aboveground buildings in cold climates due to infiltration. This consequently creates a high potential case for the underground building to reduce the energy demand, due to the absence of this infiltration.

For every case 200 calculations are made that provide a mean and standard deviation of the annual energy demand. Uncertainty analysis of the results show that in most cases the worst underground building performs better than the best aboveground building.

Based on the reviewed results and methodology, some recommendations can be made for future work concerning identification of the energy reduction potential of underground buildings compared to aboveground buildings.

- A higher accuracy can be obtained by performing calculations using simulation software which contain a more accurate ground heat transfer calculation. More knowledge can be obtained on the daily pattern by performing hourly calculations and by providing occupancy schedules. Also, a better understanding of the local microclimate in underground buildings is necessary to identify whether lower peak heating and cooling is required.
- The method of applying weather data from a location that corresponds with a certain climate should also be reconsidered, as the difference in weather data between different locations in the same climate can be very large and therefore one location does not accurately represent a climate. Average values for more locations in one climate can make a better representation.
- More quantitative information on the annual energy demand of semi underground buildings is required, as these buildings can benefit from the thermal advantages of the ground while also allowing daylight to enter the building.

5. REFERENCES

[1] J. Godard, "Urban underground space and benefits of going underground," in *World Tunnel Congress 2004 and 30th ITA General Assembly*, Singapore, 2004.

[2] J. Admiraal, "A Bottom-up Approach to the Planning of Underground Space," Gouda.

[3] E. Horvat, "Going beyond the frontier of urban space, use of the subsurface space".

[4] F. Chow, T. Paul, I. Vähäaho, B. Sellberg and L. Lemos, "Hidden Aspects of Urban Planning: Utilisation of Underground Space," in *Conference on Soil Structure Interaction in Urban Civil Engineering*, Zurich, 2002.

[5] M. Khair-El-Din and Abd-El-Hamid, "Earth Sheltered Housing: An Approach to Energy Conversation in Hot Aird Areas," *Architecture and Planning*, vol. 3, pp. 3-18, 1991.

[6] F. Wang and Y. Liu, "Thermal environment of the courtyard style cave dwelling in winter," *Energy and Buildings*, vol. 34, pp. 985-1001, 2002.

[7] L. Boyer, "Earth Sheltered Structures," *Ann. Rev. Energy*, vol. 7, pp. 201-219, 1982.

[8] R. Sterling and J. Godard, "Geoenengineering considerations in the optimum use of underground space".

[9] B. Todorovic and B. Despotovic, "Development of calculation procedure for heat losses of underground spaces," in *Proceedings of the Transactions of the 30th HVAC Congress*, Belgrade, 1999.

[10] A. Anselm, "Passive annual heat storage principles in earth sheltered housing, a supplementary energy saving system in residential housing," *Energy and Buildings*, vol. 40, pp. 1214-1219, 2008.

[11] A. Al-Temeemi and D. Harris, "A guideline for assessing the suitability of earth-sheltered mass-housing in hot-arid climates," *Energy and Buildings*, vol. 36, pp. 251-260, 2004.

[12] EN-ISO 13790, "Energy performance of buildings - Calculation of energy use for space heating and cooling (ISO 13790:2008)," European Committee for Standardization, 2008.

[13] M. Peel, B. Finlayson and T. McMahon, "Updated world map of the Köppen-Geiger climate classification," *Hydrol. Earth Syst. Sci.*, vol. 11, pp. 1633-1644, 2007.

[14] M. Deru, K. Field, D. Studer, K. Benne, B. Griffith and P. Torcellini, U.S. Department of Energy Commerical Reference Building Models of the National Building Stock, Colorado: National Renewable Energy Laboratory, 2011.

[15] CIBSE, CIBSE Guide A: Environmental design, Norwich: CIBSE, 2006.

[16] S. Ocaña and I. Guerrero, "Comparison of analytical and on site temperature results on Spanish traditional wine cellars," *Applied Thermal Engineering*, vol. 26, pp. 700-708, 2006.

[17] C. Hopfe, "Uncertainty and sensitivity analysis in building performance simulation for decision support and design optimization," Eindhoven University of Technology, Eindhoven, 2009.

[18] K. J. Lomas and H. Eppel, "Sensitivity analysis techniques for building thermal simulation programs," *Energy and Building*, vol. 19, pp. 21-44, 1992.

[19] K. Labs, "Underground Building Climate," *Solar Age*, vol. 4, no. 10, 1979.

[20] Solar Energy Laboratory, "TRNSYS 17.1. A transient systems simulation program," Solar Energy Laboratory, University of Wisconsin-Madison, Madison, 1990.

[21] J. Myers, Research design and statistical analysis, Lawrence Erlbaum Associates, 2003.

[22] M. Staniec and H. Nowak, "Analysis of the earth-sheltered buildings' heating and cooling energy demand depending on type of soil," *Archives of Civil and Mechanical Engineering*, vol. XI, no. 1, pp. 221-235, 2011.

[23] T. McKnight and D. Hess, Physical Geography: A Landscape Appreciation, Upper Saddle River, New Jersey: Prentice Hall, 2000.

Appendix A – CLIMATE DESCRIPTIONS

Table A. 1: Description of the Köppen-Geiger climate classifications [13], [23].

GROUP A: Tropical/megathermal climates			
Singapore	Af	Singapore	Tropical rainforest
	Am		Tropical monsoon
Thailand	Aw	Bangkok	Tropical wet and dry or savanna
GROUP B: Dry (arid and semiarid) climates			
U.S.A.	BWh	Phoenix	Low latitude desert
	BWk		Middle latitude desert
U.S.A.	BSh	San Antonio	Low latitude steppe
U.S.A.	BSk	Colorado Springs	Middle latitude steppe
GROUP C: Temperate/mesothermal climates			
Spain	Csa	Seville	Dry summer subtropical
	Csb		Mediterranean
	Cwa		Humid subtropical
South Africa	Cwb	Johannesburg	Temperate highland tropical with dry winters
	Cwc		Temperate highland tropical with dry winters
U.S.A.	Cfa	Jacksonville	Humid subtropical
The Netherlands	Cfb	Amsterdam	Maritime Temperate or Oceanic
	Cfc		Maritime subartic or Subpolar Oceanic
GROUP D: Continental/microthermal climates			
	Dsa		Hot Summer Continental
USA	Dsb	Great Falls	Warm Summer Continental or Hemiboreal
	Dsc		Continental Subartic or Boreal (Taiga)
	Dsd		Humid Subartic
	Dwa		Hot Summer Continental
U.S.A.	Dwb	Minneapolis	Warm Summer Continental or Hemiboreal
	Dwc		Continental Subartic or Boreal (Taiga)
	Dwd		Continental Subarctic with extremely severe winters
U.S.A.	Dfa	Kansas City	Hot Summer Continental
Finland	Dfb	Helsinki	Warm Summer Continental or Hemiboreal
Finland	Dfc	Sodankylae	Continental Subartic or Boreal (Taiga)
	Dfd		Continental Subarctic with extremely severe winters
GROUP E: Polar climates			
Canada	ET	Inukjuak	Tundra
	EF		Ice Cap
Climates with a corresponding country and location are used in the calculation.			

III. Underground buildings BESTEST Case study

Underground buildings
BESTEST Case study

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1. INTRODUCTION

To verify the energy reduction potential of underground buildings in the former study described in *Chapter I*, and to investigate the daily patterns of the energy performance of both buildings, the BESTEST Case 900 is simulated using the software program TRNSYS [2]. The building is simulated for the aboveground situation and corresponding underground situation.

2. METHODOLOGY

2.1. BESTEST Case 900 characteristics

For simulation of an aboveground- and underground building, the BESTEST Case 900 is used [3]. Several of the original parameters are adjusted, such as the infiltration rate and conductivity of the constructions (**Table 1**). The changed values correspond to a good insulated building with a very small amount of infiltration. These changes will lessen the energy reduction potential of underground buildings, but take into account the advances that are made for aboveground buildings and their increase in energy efficiency.

Table 1: BESTEST Case 900 Characteristics

BESTEST C900	AB*	UB*
Floor area [m^2]	48	48
Heating set-point	20 on / 15 off	
Cooling set-point	24 on / 100 off	
Ventilation rate [1/h]	0.2 on / 0 off	
Infiltration rate[3] [1/h]	0.1	**0**
Internal gains: radiative [kJ/hr]	432	432
Internal gains: convective [kJ/hr]	288	288
*Aboveground building / Underground building		

	AB*	UB*
Ground floor [W/m^2K]	0.205	0.205
External wall [W/m^2K]	0.21	0.21
Roof [W/m^2K]	0.16	0.16
U-value window [W/m^2K]	1.43	x
Solar heat gain coefficient	0.605	x
Thermal conductivity ground [W/mK]	x	1.95
Density ground [kg/m^3]	x	2075
Specific heat capacity ground [J/kgK]	x	1450

2.2. Climates

Calculations are made for three different climates (**Table 2**). Ground input parameters for the three climates are calculated using the Labs equation [4]. A desert climate (BWh, location: **Phoenix**), maritime temperate climate (Cfb, **Amsterdam**) and hemiboreal climate (Dfb, **Helsinki**) are simulated to show differences in the energy performance in different climates.

Table 2: Three different climates with corresponding ground characteristics.

	BWh	Cfb	Dfb
Deep earth temperature [˚C]	22.46	9.46	4.44
Amplitude of surface temperature [˚C]	10.97	7.14	11.89
Day of minimum surface temperature	350	16	45

2.3. TRNSYS simulation

Building energy simulation is carried out using TRNSYS. The BESTEST Case 900 is modeled using an integrated module inside Google SketchUp [5], which allows easy 3D modeling. Both the aboveground- and underground buildings have the same dimensions, but the underground building excludes windows. A visualization of both the models can be seen in **Figure 1**. Further information on the BESTEST Case can be found in [3].

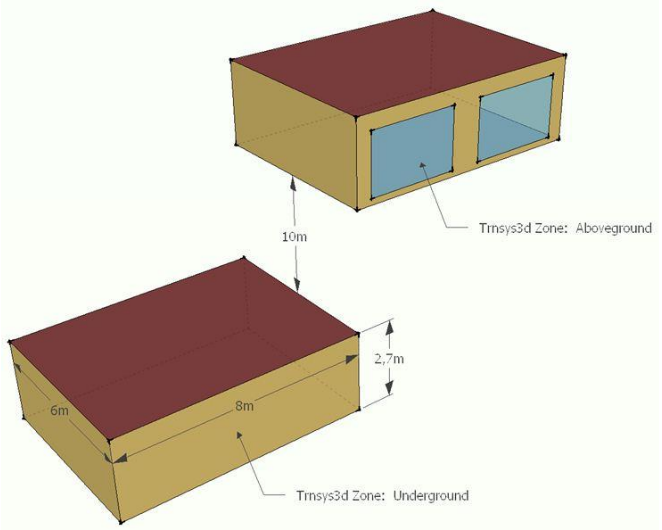


Figure 1: Model of the aboveground- and underground building in Google SketchUp.

2.4. Ground heat transfer calculation

Inside TRNSYS, the module "Type 1244: Multizone basement model" models the heat transfer from a horizontal or vertical surface (typically, but not limited to a basement) to the surrounding soil. The heat transfer is assumed to be conductive only and moisture effects are not accounted for in the model. The model relies on a 3-dimensional finite difference model of the soil and solves the resulting inter-dependent differential equations using a simple iterative method. The model takes the heat transfer into or out of the building at the outside surface for each zone, calculates the fully 3-D soil temperature profile, and then gives as output the average under floor surface temperature for each zone. The near-field soil temperatures are affected by the heat transfer from the slab. The far-field soil temperatures are only affected by the surface conditions (time of year) and depth. The model in return calculates the slab/ground interface temperature, which is passed back to the building model as an input [6].

3. RESULTS AND DISCUSSION

The aboveground- and underground building situation of the BESTEST case 900 are simulated using TRNSYS for three different climates. The energy demand for heating and cooling of the different cases are shown in **Figure 2**.

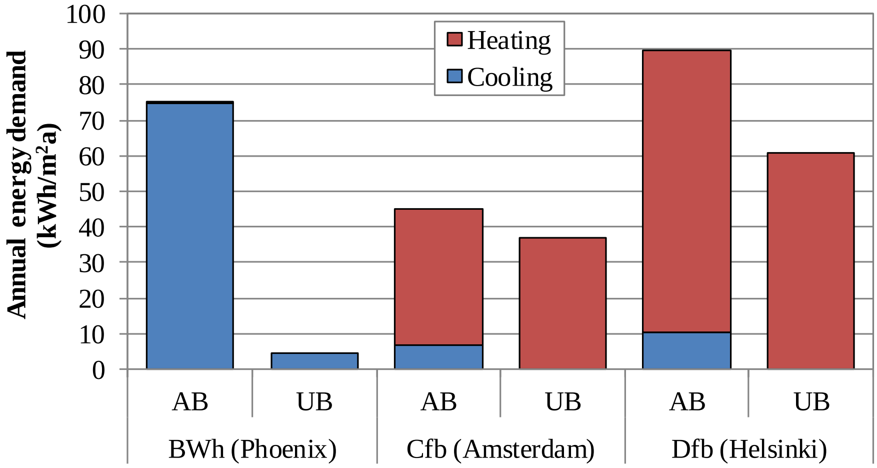


Figure 2: Annual energy demand of the aboveground- and underground situation of the BESTEST case 900 for three different climates.

In all cases the underground building performs better than the aboveground counterpart. Nonetheless, it can be seen that there exist large differences in energy demand of the aboveground- and underground building for different climates. The desert climate (BWh) shows a high potential in the energy reduction of the aboveground building, by placing it underground. While the maritime temperate climate (Cfb) shows only a small reduction in the annual energy demand. The hemiboreal climate (Dfb) shows a higher energy reduction than the maritime temperate climate (Cfb), but smaller reduction than in the desert climate (BWh).

The explanation between these differences can be found when investigating the climate characteristics. In **Figure 3** to **Figure 5**, temperature profiles are shown for the ambient temperature, the zone temperature of the underground building, and the boundary temperature of the underground wall in three different climates. The high energy reduction potential of the desert climate follows from the high underground temperature of around 23˚C. The underground temperature lies between the heating- and cooling set points, which causes the transmission losses to be very low. Therefore little energy is required to keep the building at a comfortable indoor temperature in comparison to the aboveground building, where cooling is needed due to the high outside temperatures.

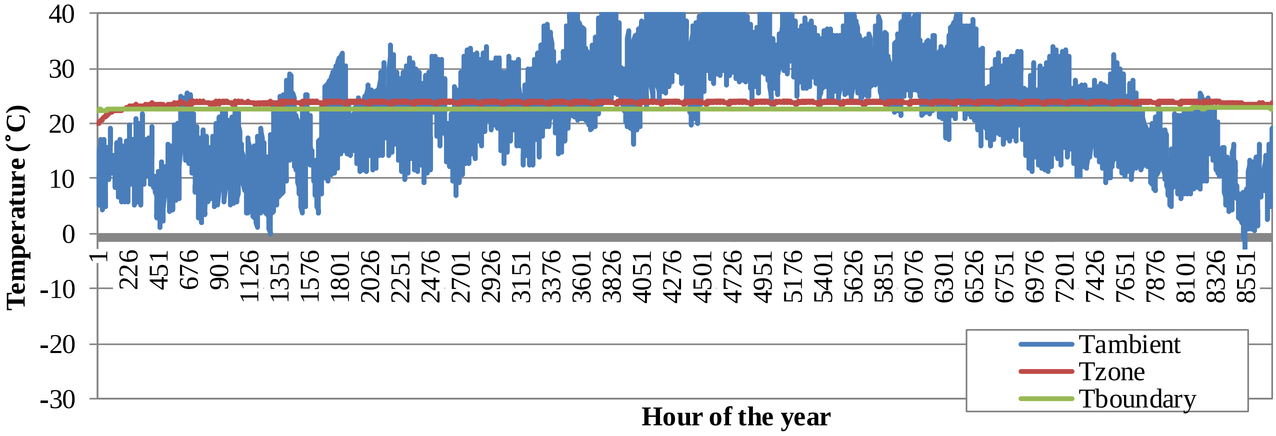


Figure 3: Temperature profiles (outside, zone and boundary wall) of the underground building in the desert climate (BWh).

The underground temperatures of the maritime temperate and hemiboreal climates are much lower and therefore much energy is needed for heating the underground building. This is also true for the aboveground situation, where even more heating is needed during the winter due to even lower temperatures than the underground temperatures. While during the summer temperatures are somewhat higher than the underground temperature and therefore little cooling is also required for the aboveground building.

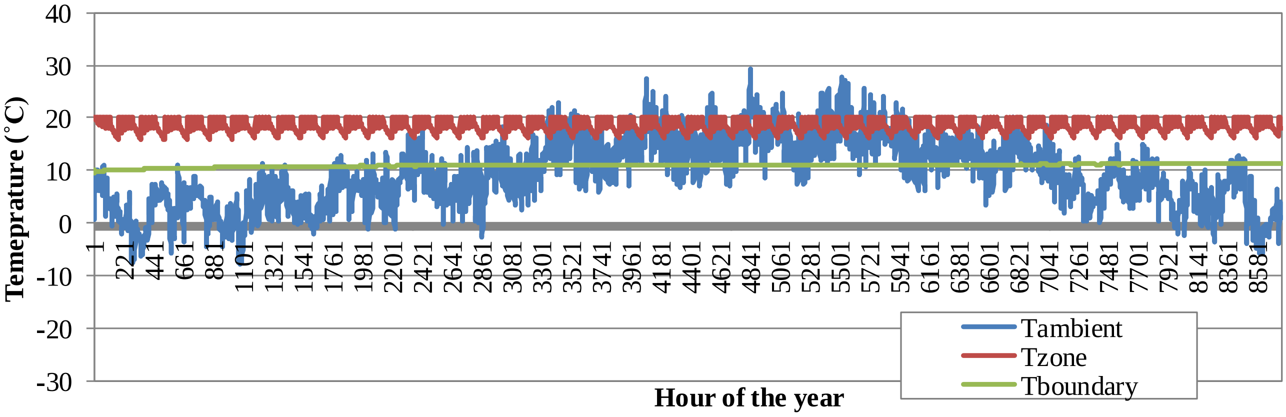


Figure 4: Temperature profiles (outside, zone and boundary wall) of the underground building in the maritime temperate climate (Cwb).

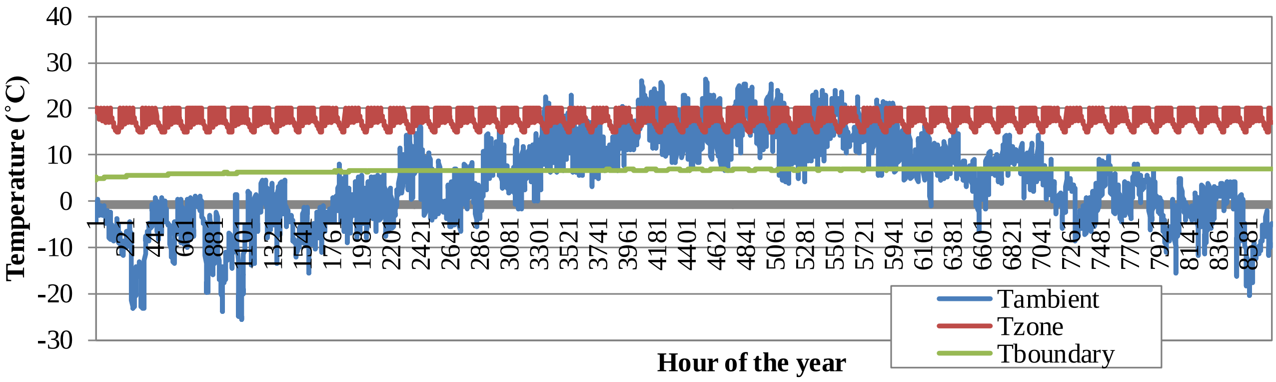


Figure 5: Temperature profiles (outside, zone and boundary wall) for the underground building in the hemiboreal climate (Dfb).

Although the underground temperature is a very important factor in reducing the energy demand of the underground building, there are several other energy flows that affect the energy reduction potential. To get a better understanding of how the energy gains and losses influence the energy performance of an aboveground- and underground building, the daily pattern of the energy flows is important. In **Figure 6** and **Figure 7**, the energy flows and temperatures of the aboveground- and underground building are shown for the desert climate (BWh) on the 22th of July.

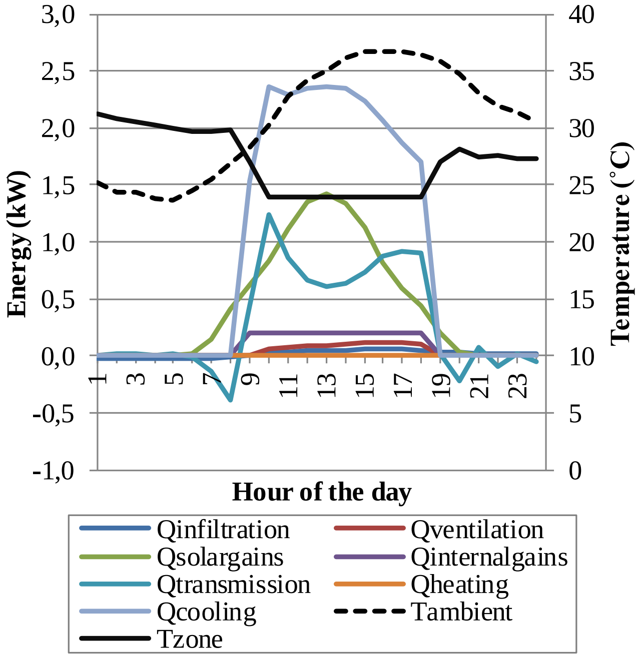


Figure 6: Energy balance and temperatures of the aboveground BESTEST case in a desert climate (BWh) on the 22th of July.

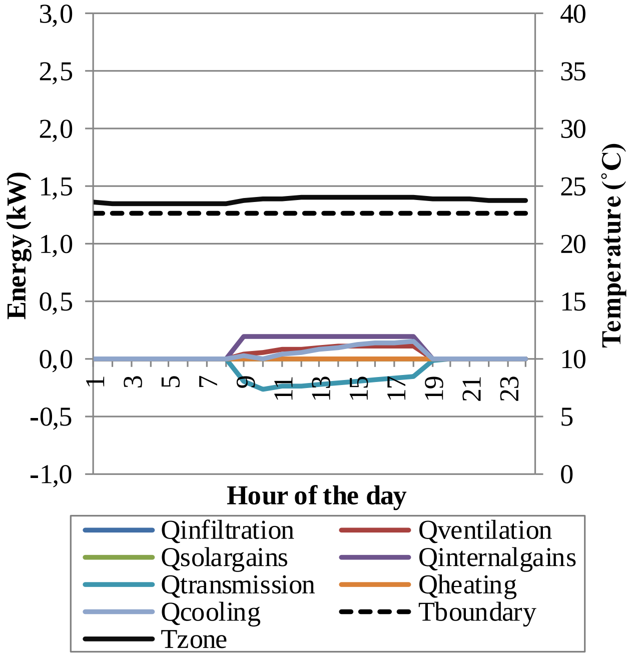


Figure 7: Energy balance and temperatures of the underground BESTEST case in a desert climate (BWh) on the 22th of July.

From the graphs it follows that the underground building has a boundary temperature of 23˚C and therefore the transmission losses are very low. Only due to the ventilation gains and internal gains during the day, the underground building requires only a small amount of energy for cooling. In comparison, the aboveground building is adjacent to very high outdoor temperatures during this summer day. To establish and maintain the maximum set-point temperature of 24˚C, a large amount of cooling is needed. But in this case, not only the high outdoor temperatures are cause of the large difference in the cooling demand. Although the internal gains and ventilation gains are equal to the underground building, the solar gains present during the day cause the cooling demand to be much higher. The infiltration in this case has very little influence on the energy demand. For the aboveground situation in the desert climate (BWh) the daily profile is almost the same throughout the year, which means that the increase in energy demand is quite stable.

For the hemiboreal climate (Dfb) the outdoor temperatures are below 0˚C for a large time interval, while it is somewhat warmer during the summer. In **Figure 8** and **Figure 9** the energy balance and temperatures are shown of a particular summer day.

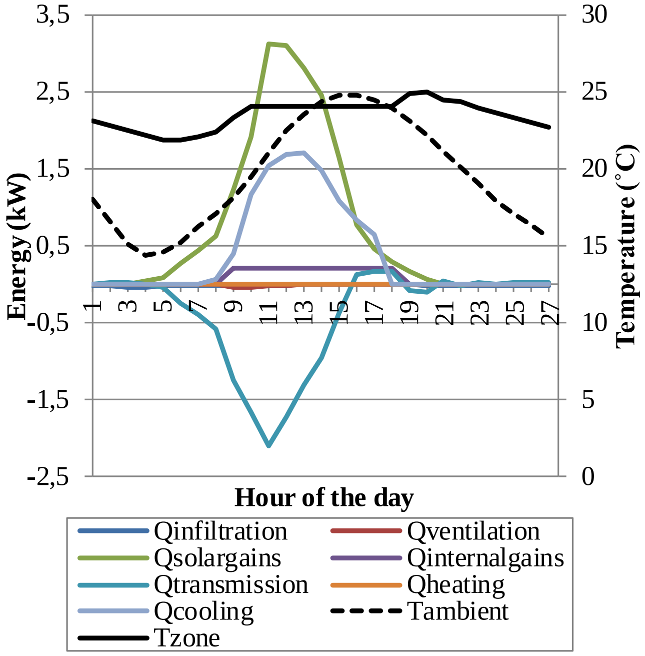


Figure 8: Energy balance and temperatures of the aboveground BESTEST case in a hemiboreal climate (Dfb) on the 22th of July.

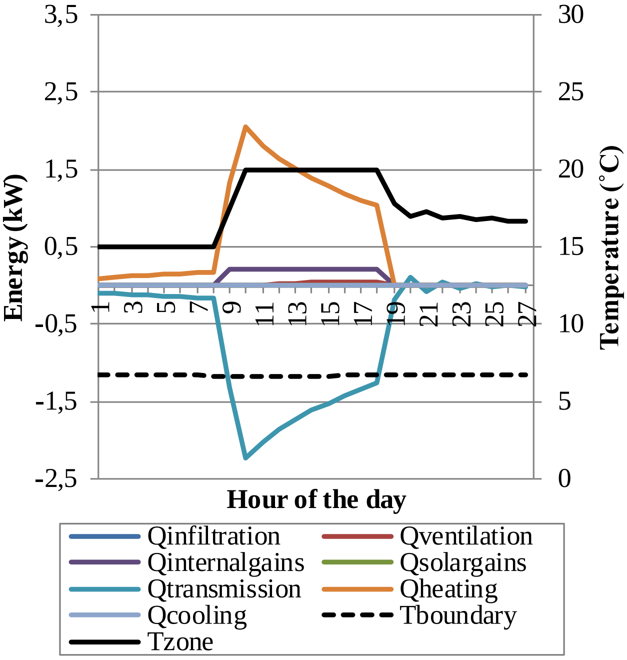


Figure 9: Energy balance and temperatures of the underground BESTEST case in a hemiboreal climate (Dfb) on the 22th of July.

In comparison to the desert climate (BWh), the underground building requires a much larger amount of energy to maintain a comfortable temperature. This is largely due to the much lower underground temperature of around 7˚C throughout the year. A building with more internal gains would reduce the energy need for heating in this case. The aboveground building on the other hand requires cooling during the summer due to the high solar gains that are present during the afternoon.

The daily profiles of the maritime temperate climate (Cfb) are similar to the daily profiles of the hemiboreal climate (Dfb). The only difference is that the transmission losses are somewhat larger in the hemiboreal climate (Dfb) due to the lower outdoor- and ground temperatures.

The energy reduction potential of the hemiboreal climate (Dfb) is somewhat higher than for the maritime temperate climate (Cfb). The reason for this is the relatively higher energy demand of the aboveground building in the hemiboreal climate (Dfb). The lower outdoor temperatures during the winter seem to have a larger negative effect on the energy demand than the lower ground temperature in the hemiboreal climate.

4. CONCLUSION

The energy reduction potential of underground buildings has been verified by simulating the BESTEST Case 900 with the software program TRNSYS. Although several building characteristics and inputs are dissimilar to the calculations performed in the former study, high energy reduction is perceived between the energy demand of the aboveground- and underground building. Furthermore, hourly calculations have allowed a better understanding of the daily pattern of the energy performance of the aboveground- and underground building.

The underground temperature seems to be a very important factor for reducing the energy demand of the underground building. An underground temperature that is near the heating- and cooling set-points is most likely to result in a building with low energy requirement. A low energy demand can therefore be achieved in climates that have beneficial underground temperatures. Nonetheless, the energy reduction potential of underground buildings compared to aboveground buildings is not based on the low energy demand of underground buildings, but on the difference between the annual energy demand of the aboveground- and

underground building. Therefore, it is not useful to build an underground building when the aboveground building counterpart is very energy efficient and has a low energy demand.
Simulations should therefore be carried out if considering and underground building instead of an aboveground building. The energy reduction potential depends on the location (climate) of the building, but also the other building characteristics, such as internal gains and ventilation can have a large influence on the energy demand.

Some recommendations can be made, which follow from simulating and modeling underground buildings with the software program TRNSYS.

- In the underground situation, it is impossible to model walls that are not perpendicular. This impossibility causes an inaccuracy in modeling many buildings. The modeling method that is needed in TRNSYS should therefore be adjusted to include the feature of modeling different angles in a building façade.
- The modeling of an underground building is very time consuming and unclear. Every surface of a zone has to be connected several times throughout different module types. A more efficient way would be to let TRNSYS do this automatically.

5. REFERENCES

[1] C. van Dronkelaar, J. Hensen, D. Cóstola and R. Mangkuto, "Underground buildings - Potential in terms of energy reduction," Eindhoven University of Technology, 2013.

[2] Solar Energy Laboratory, "TRNSYS A Transient System Simulation Program," University of Wisconsin-Madison, 2012.

[3] R. Judkoff and J. Neymark, "International Energy Agency Building Energy Simulation Test (BESTEST) and Diagnostic Method," National Renewable Energy Laboratory, Golden, Colorado, 1995.

[4] K. Labs, "Underground Building Climate," *Solar Age*, vol. 4, no. 10, 1979.

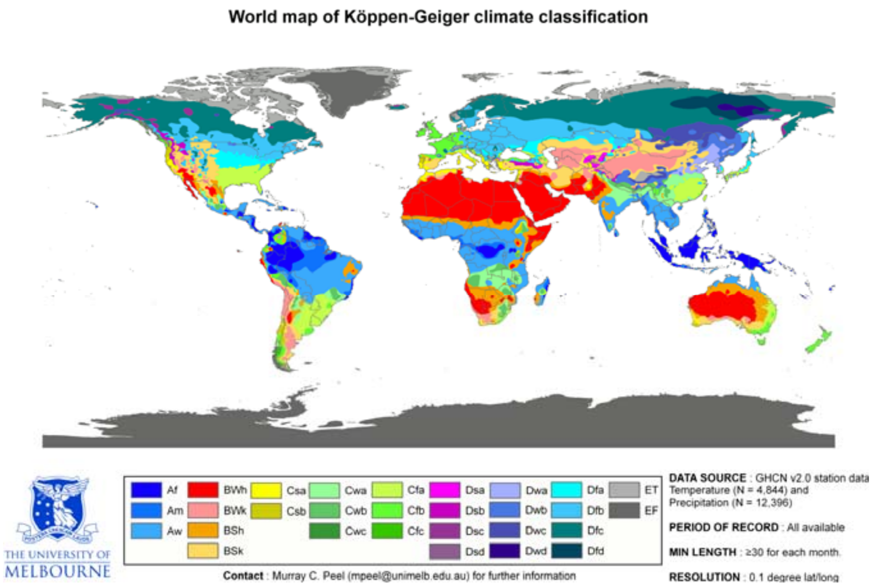
[5] Trimble Building, "SketchUp Pro," Trimble Navigation Limited, 2012.

[6] TESS Experts in Energy Modeling & Analysis, "TESS Component Libraries: General Descriptions".

IV. Underground buildings

Underground building examples

Climate classification



Peel, M. C. and Finlayson, B. L. and McMahon, T. A. (2007). "Updated world map of the Köppen–Geiger climate classification". Hydrol. Earth Syst. Sci. 11: 1633–1644. ISSN 1027-5606. (direct: Final Revised Paper)

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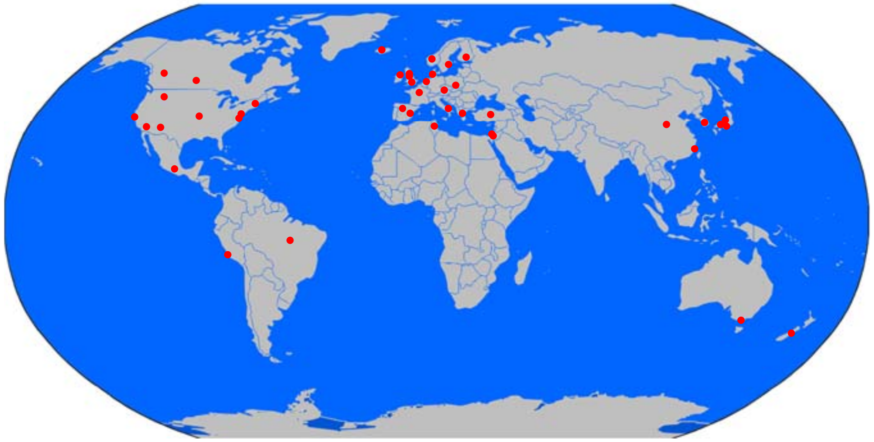
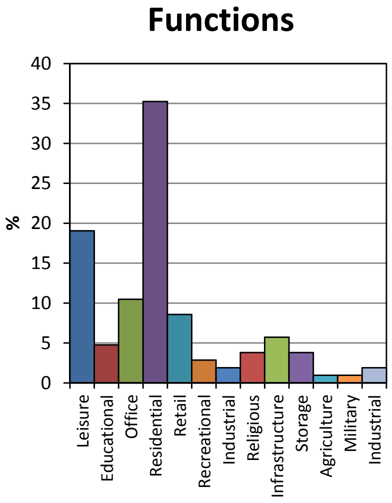
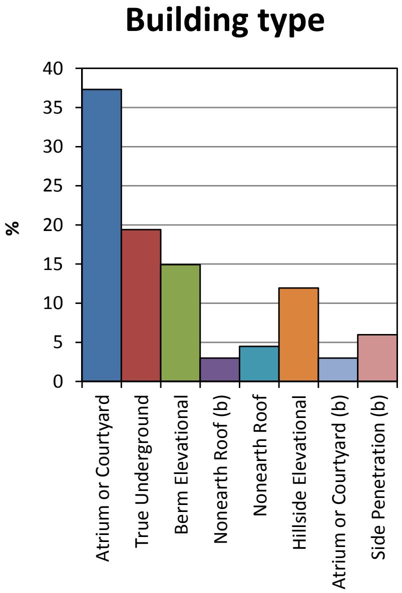
71 Examples

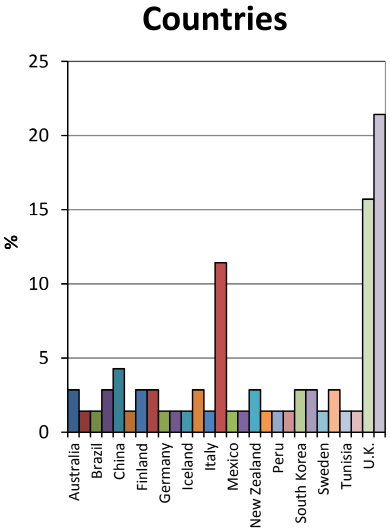


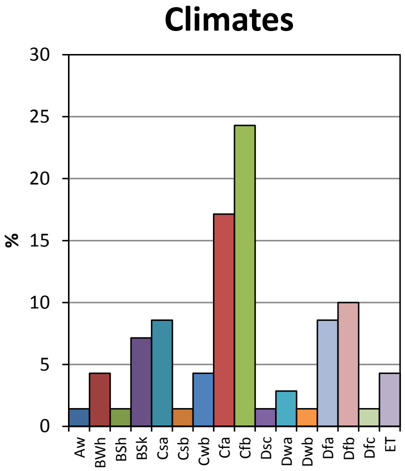
Function and building type


Functions


Building type

Countries and Climates


Countries


Climates

Name of the building

00

Architect | Location | Year of completion

Function(s)

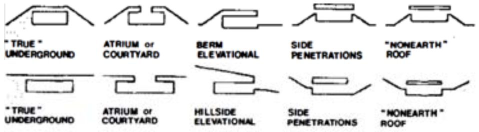
Climate description (Climate code)

- ≤ Disadvantages
- ≥ Advantages

Below ground level	**≈ %**
Surface to ground	**≈ %**
Depth	**≈ m**

Pictures of the building

Building type



\# Reference

Citylink Mall

01

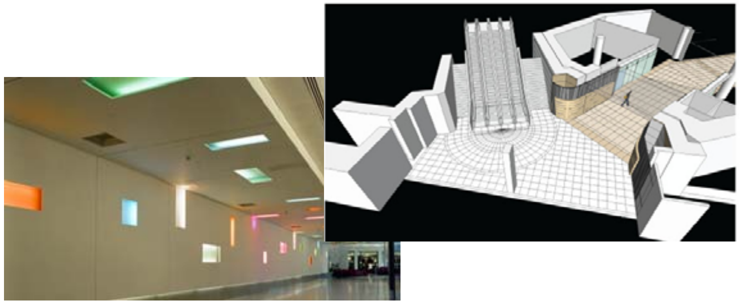
Kohn Pedersen Fox and LPT Architects|Singapore, Singapore | 2000

Retail

Tropical rainforest (Af)

- ≥ CityLink Mall is the unique retail component of the One Raffles Link development. It provides around 60,000 sq.ft. of retail space in an air-conditioned subterranean mall, and links One Raffles Link to the City Hall and Esplanade MRT Station.
- ≥ The stunning subterranean mall with over 50 shops, offers international fashion names, exquisite gifts & accessories, home accessories and some of the best eateries in Singapore.
- ≥ Daylight is delivered to the space by glazed pavilions sited on the War Memorial gardens, which creates a bright and cheery feel.

Below ground level	**≈ 100%**
Surface to ground	**≈ 40%**
Depth	**≈ 300m**



\# http://www.contrib.andrew.cmu.edu/~igaur/
\# http://www.citylinkmall.com/about

Cathedral Metropolitana

02

Oscar Niemeyer | Brasilia, Brazil | 1970

Religious

Tropical wet (Aw)

- The cathedral is a hyperboloid structure constructed from 16 concrete columns, weighing 90 tons each.
- The exterior of the cathedral resembles the circular plan and ribbed structure of Liverpool Metropolitan Cathedral, but the latter is clad in solid material, while the Cathedral of Brasília allows light in and out for almost the full height of the ribs.

Below ground level	**≈ 20%**
Surface to ground	**≈ 20%**
Depth	**≈ 2m**

\# E. von Meijenfeldt, Below Ground Level, 2003
\# http://en.wikipedia.org/wiki/Cathedral_of_Bras%C3%ADlia

Troglodyte

03

Matmata, Tunisia | knowledge of existence from 1967

Residential

Dry Desert (BWh)

- A large pit is dug, where around the perimeter of this pit artificial caves are dug to be used as rooms, with some homes comprising multiple pits, connected by trench-like passageways.
- A tourist attraction, because filming is done in one such a troglodyte home for the Star Wars movies.

Below ground level	**≈ 100%**
Surface to ground	**≈ 60%**
Depth	**≈ 6m**

\# http://chinablog.cc/2009/02/yaodong-cave-dwellings-on-loess-plateau/
\# http://en.wikipedia.org/wiki/Yaodong

Pachacamac hill house

04

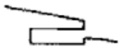
Longhi Architects | Pachacamac, Lima, Peru| 2012

Residential

Dry Desert (BWh)

Below ground level	**≈ 70%**
Surface to ground	**≈ 70%**
Depth	**≈ 4m**

- Because it is entirely constructed of stone, it will last thousands of years. It's also almost entirely underground, which will make it able to withstand extreme climate change in the meantime.
- Locally quarried, smoothed and polished stone also is used inside to construct the interior walls and even some shelving. For its longevity, it will certainly win LEED points: it's not going to the landfill any decade soon. Its energy use is moderated by being underground. So it's green.
- For what amounts to a 10,000 square foot underground bunker, light is able to get down into the entirely stone hewn space fairly well. The dining room table is a huge singular stone set permanently in place.



HILLSIDE ELEVATIONAL

http://www.homedesignfind.com/green/10000-square-foot-underground-bunker-will-remain-forever/
http://www.longhiarchitect.com/home.html

Coober Pedy

05

- | Coober Pedy, Australia | 1800's

Residential

Dry Desert (BWh)

Below ground level	**≈ 100%**
Surface to ground	**≈ 100%**
Depth	**≈ 10m**

- This small town in the middle of nowhere, Australia, is home to some of the strangest houses on Earth. A combination of climactic conditions and the existence of opal mining in the region have literally driven the residents underground. Everything from residences to churches are carved out of the ground as the above images show. The place is something of a tourist attraction, with underground hotels as well as a golf course above ground – though golf is played at night due to the regional heat!

"TRUE" UNDERGROUND

http://weburbanist.com/2007/09/30/7-underground-wonders-of-the-world-labyrinths-crypts-and-catacombs/

Above Below

Matthew Fromboluti | Lavender Pit Mine in Bisbee, Arizona, U.S.A. | Concept

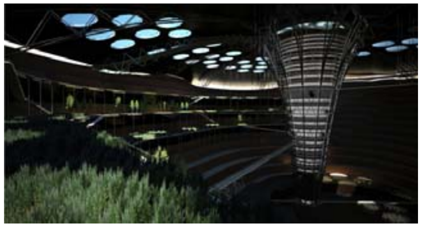
06

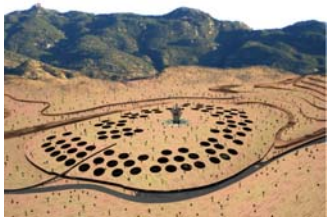
Residential, Office, Agriculture, Leisure

Dry Steppe
(Bsh)

- Through use of many simple, passive systems, the entire complex is a sustainable, underground oasis in the desert, with the area above reclaimed for nature, and the space below a unique opportunity for human use.
- The building is completely self-sustaining, with its own power source, water recycling system, and mechanisms such as a solar chimney to control the artificial climate.

Below ground level	**≈ 95%**
Surface to ground	**≈ 60%**
Depth	**≈ 50m**





\# http://www.evolo.us/architecture/skyscraper-or-sustainable-underground-society/

\# http://www.frombo.com/folio-Evolo10.html

Noashima art museum

Tadao Ando | Naoshima, Kagawa, Japan | 1995

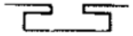
07

Leisure, Residential

Dry Steppe
(BSk)

- The composition of the Museum's main building consists of three overlapping cubes and a circle, with a rectangular guest wing attached at an angle to it. The simple geometrical volumes of the Museum are built within the hillside so as not to disturb the beauty of the natural landscape but to become a part of it.
- Connected to this corridor is an oval shaped cut out volume of which in the center is a pool of still water filled to its edges reflecting the surrounding volume and the sky above.

Below ground level	**≈ 100%**
Surface to ground	**≈ 60%**
Depth	**≈ 10m**



\# E. von Meijenfeldt, Below Ground Level, 2003

\# http://www.galinsky.com/buildings/naoshima/index.htm

Central Pre-mix company

Walker McGough Foltz Lyerla architects | Spokane, Washington, U.S.A. | 1980

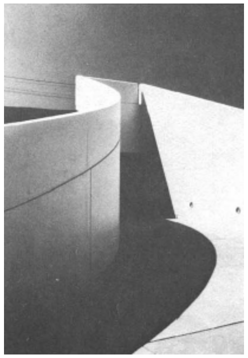
08

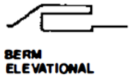
Leisure, Office

Dry Steppe
(BSk)

- The earth is used effectively in this project to achieve energy conservation. Heat transfer by means of infiltration is virtually eliminated by the monolithic earth covering
- In Spokane, air temperatures vary between -23 and 48°C. Temperatures in the earth at a depth of 2 m vary from 5 to 16°C. According to the architects
- 50% reduction in the amount of energy consumed, compared to a conventionally constructed façade building of the same size and function.

Below ground level ≈ 60%
Surface to ground ≈ 70%
Depth ≈ 6m





Barker, M., 1986. Using the Earth to Save Energy: Four Underground Buildings. Tunneling and Underground Space Technology
http://www.cprestress.com/projects/63/

Cave homes in Cappadocië

Cappadocië, Central Anatolia, Turkey | > 1000 B.C.

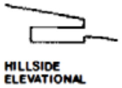
09

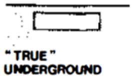
Residential

Dry Steppe
(BSk)

- Cappadocia contains several underground cities (see Kaymaklı Underground City), largely used by early Christians as hiding places before Christianity became an accepted religion.
- 260km^2 with 200+ underground villages and tunnel towns complete with hidden passages, secret rooms and ancient temples

Below ground level ≈ 0%
Surface to ground ≈ 70%
Depth ≈ ?m





http://www.turkije-info-site.nl/capadocie-turkije.html

Messa Verde

10

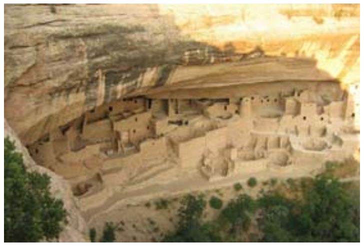
- | Cortez, Colorado, U.S.A. | 12th Century

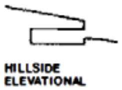
Dry Steppe
(BSk)

Residential

- It may be the most significant archeological preserve of Native American culture in the United States. In the 12th century, the Anasazi start building houses in shallow caves and under rock overhangs along the canyon walls. Some of these houses were as large as 150 rooms. The most famous of these are called Cliff Palace and Spruce Tree House. By 1300, all of the Anasazi had left the Mesa Verde area, but the ruins remain almost perfectly preserved.

Below ground level	**≈ 0%**
Surface to ground	**≈ 30%**
Depth	**≈ ?m**





\# http://www.touropia.com/cave-dwellings/

Teruel-Zilla

11

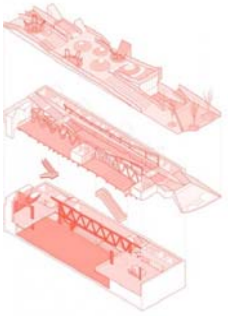
Mi5 + PKMN | Tereul, Aragón, Spain | 2012

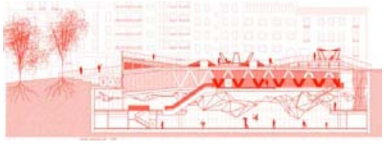
Dry Steppe
(BSk)

Leisure

- Teruel-Zilla is a three-story underground leisure and rec center for the youth of Teruel, Spain. The spot was once home to a public market building, but it was becoming obsolete, so the town decided to make way for something more useful. Mi5 + PKMN designed a leisure center to take the place of the market building, but buried it underground in order to create open space in the public square. The landscaped area on the ground floor is a series of stepped planes, ramps and staircases which creates a new urban topology that encourages interaction, activity and community. Burying the center underground protects it from the warm climate and leaves the ground floor for vegetation, thus helping reduce energy use and heat island effect.

Below ground level	**≈ 95%**
Surface to ground	**≈ 90%**
Depth	**≈ 10m**





\# http://inhabitat.com/teruel-zilla-is-an-underground-leisure-lair-inspired-by-dinosaurs-in-spain/teruel-zilla-mi5-pkmn-9/
\# http://www.mi5arquitectos.com/mi5-architects-plaza-teruel/

Cave-homes

12

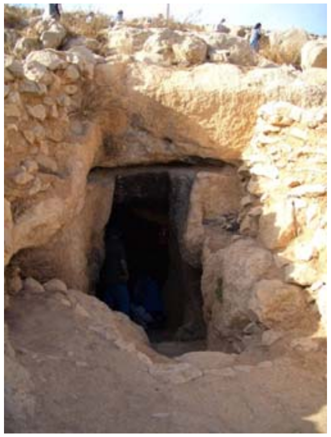
- | Israel| -

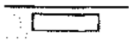
Residential

Dry-summer subtropical (Csa)

- “Bir al-Id used to be home to 397 Palestinians. The village residents maintained a unique way of life, drawing water from wells and pits in the area around their huts, tents and cave dwellings.
- “These people live in caves – some out of poverty, some out of preference. They keep flocks like Bedouin do but they also practice subsistence agriculture. They split their time between a town called Yatta and the caves.

Below ground level	≈ **100%**
Surface to ground	≈ **95%**
Depth	≈ **4m**





http://www.rhr-na.org/blog/?p=789

Hebridean Earth House

13

Mickey Muennig | Big Sur, California, U.S.A. | 1971

Residential

Dry-summer subtropical (Csa)

- The structure of the home is so that it maximizes the views across the islands.

Below ground level	≈ **80%**
Surface to ground	≈ **70%**
Depth	≈ **3m**

http://www.hebhide.co.uk/

Casa de Retiro Espiritual

14

Emilio Ambasz | Sevilla, Spain | 1980

Residential

Dry-summer subtropical (Csa)

- An underground "canopy" of fiberglass panels extends horizontally as a ten foot cornice from the wall's top to keep water from soaking the ground around the house.
- All practical needs and services (kitchen, baths, storage, etc.) are satisfied by geometric containers placed into the ground. Sleeping is in either some of the living areas or in the sleeping alcoves contained within the sides.

Below ground level	**≈ 70%**
Surface to ground	**≈ 60%**
Depth	**≈ 5m**

\# http://www.emilioambaszandassociates.com/portfolio/portfolio.cfm?Pid=81
\# http://www.pushpullbar.com/forums/showthread.php?4480-USA-Emilio-Ambasz

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Petra (historical city)

15

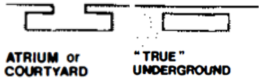
Petra, Jordan, Israel | 6th century B.C.

Residential

Dry-summer subtropical (Csa)

- The site remained unknown to the Western world until 1812, when it was introduced by Swiss explorer Johann Ludwig Burckhardt.
- The area is visited by flash floods and archaeological evidence demonstrates the Nabataeans controlled these floods by the use of dams, cisterns and water conduits. These innovations stored water for prolonged periods of drought, and enabled the city to prosper from its sale.

Below ground level	**≈ 0%**
Surface to ground	**≈ 70%**
Depth	**≈ ?m**



\# http://www.pbase.com/bmcmorrow/image/42241331
\# http://www.aquiziam.com/petra_images2.html
\# http://en.wikipedia.org/wiki/Petra

Aloni House

16

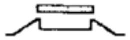
decaArchitecture | Antiparos, Paros, Greece| 2008

Residential

Dry-summer subtropical (Csa)

Below ground level ≈ 20%
Surface to ground ≈ 30%
Depth ≈ 0m

- The design of the Aloni House took a cue from these existing natural-stone walls. The architectural intervention is located in a hollow between two mountain slopes and creates a bridge, so to speak, between two contours. The house's sides disappear into the ground, blending the structure into the landscape. To the front, the land falls away, allowing one of the house's long elevations a view of the sea. There are five internal courtyards, which flood the rooms with light and shield windows and doors from stormy rainwater.



\# http://www.architonic.com/ntsht/camouflage-architecture-underground-buildings/7000497
\# http://www.deca.gr/#/en/project/265

Nuova Concordia

17

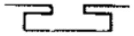
Emilio Ambasz | Castellaneta all Mare, Puglia, Italy | 2003

Residential

Dry-summer subtropical (Csa)

Below ground level ≈ 20%
Surface to ground ≈ 80%
Depth ≈ ?m

- Nuova Concordia is a residential resort community including such amenities as a shopping complex, international hotel, conference center, sporting facilities, golf course and health spa.
- To preserve the primal beauty of this site, the architect situated the buildings and roadways within landscaped berms and flowering trellises so they appear as undulating hills in the landscape. The result is a medium density development turned into a park-by-the-sea



\# http://www.emilioambaszandassociates.com/portfolio/portfolio.cfm?Pid=81
\# http://www.pushpullbar.com/forums/showthread.php?4480-USA-Emilio-Ambasz

The Estate Cave & Spa Terra

18

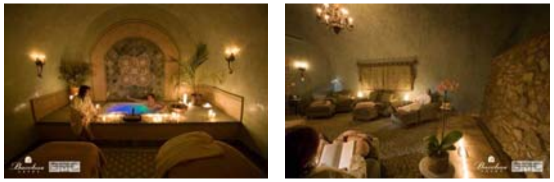
Bacchus caves | Napa, California, U.S.A. | 2007

Residential, Leisure

Mediterranean (Csb)

Below ground level ≈ 100%
Surface to ground ≈ 100%
Depth ≈ 3m

- ≥ In the hillside directly behind The Meritage Resort lies Spa Terra, a luxury spa located entirely underground in our 22000 square foot Estate Wine Cave. This Napa Valley treasure is experience unto itself. Spa guests experience the hushed serenity of the cave, with natural stone and copper water features combined with Florentine architecture and furnishings. The cave itself took 18 months to bore, plumb and construct and houses Spa Terra , an Entertainment Cave seating up to 240 guests and the Trinitas



"TRUE" UNDERGROUND

http://www.bacchuscaves.com/Featured_Meritage.asp

Earthscraper

19

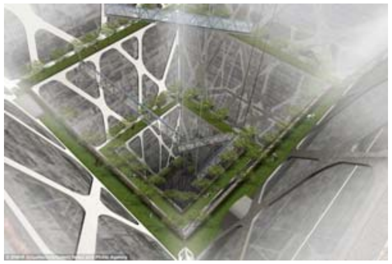
BNKR Arquitectura|Mexico city, Mexico | Concept

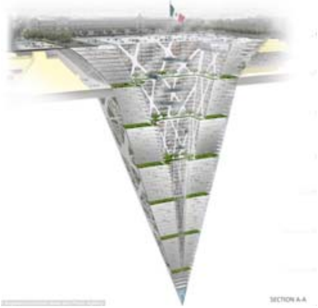
Leisure, Retail, Residential, Office

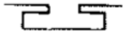
Temperate with dry winters (Cwb)

Below ground level ≈ 100%
Surface to ground ≈ 40%
Depth ≈ 300m

- ≤ Would work much better in a dry area in a northern, colder climate, where solid ground keeps you warm, and the glass top acts as a greenhouse. In a hot climate putting a building underground removes many ventilation opportunities.
- ≥ The enormous complex is intended to get round the city's planning laws, which state that buildings can be no more than eight storeys high.
- ≥ One advantage of the unusual structure is that it would create space in the centre of Mexico City, which is full of historic buildings which cannot be demolished.







ATRIUM or COURTYARD

BNKR Arquitectura http://www.bunkerarquitectura.com/
http://www.dailymail.co.uk/news/article-2048395/Earth-scraper-Architects-design-65-storey-building-300-metres-ground.html

Kölner Philharmonie

20

Busmann & Haberer | Cologne, Nordrhein-Westfallen, Germany | 1986

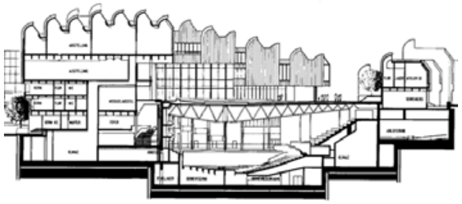
Leisure

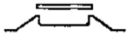
Temperate with dry winters (Cwb)

Below ground level	**≈ 100%**
Surface to ground	**≈ 70%**
Depth	**≈ 30m**

- ≤ Footstep sounds from pedestrians with high heels or noise from skateboards or rolling suitcases are transmitted from vibrating beams inside the concert hall. The reason for this is among other things the defective flooring. For this reason, the place above the theater is closed during performances.

- ≥ The concert hall is build in the building complex of the Ludwig Museum.




"NONEARTH"
ROOF

http://www.bhbfh.de/index.php?id=139&tx_kbshop_pi1[folderId]=66&tx_kbshop_pi1[v]=41&cHash=b0502e7b7be691c38c500943d5fae8d2#images|1
http://de.wikipedia.org/wiki/K%C3%B6lner_Philharmonie

Municipal Centrum Gymnasium

21

Nikken Sekkei Co | Osaka, Japan | 1996

Leisure, Office

Humid subtropical (Cfa)

Below ground level	**≈ 90%**
Surface to ground	**≈ 80%**
Depth	**≈ 30m**

- ≥ This gymnasium consists of a main arena with seating for 10,000, a sub-arena, facilities for judo and kendo, conference rooms, and a sports information area.
- ≥ For the purpose of environmental preservation and effective use of the premises, most of the building including the main arena (30m high, 110m diameter) was built underground. The roof is covered with a 1m-thick layer of soil and plants, realizing an undulating park rich in vegetation. Natural daylight and air circulation in all dry areas was insured with energy-saving techniques, such as a ventilation system that utilizes heat-insulation and isothermal effects specific to underground building


HILLSIDE
ELEVATIONAL

http://nett21.gec.jp/ESB_DATA/EN/building/html/esb-087.html
http://www.nikken.co.jp/en/projects/cultural/sports/post-1.html

Underground Metropolis (Idea)

22

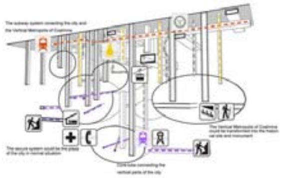
Fan Shuning, Zhang Xin| China | Idea

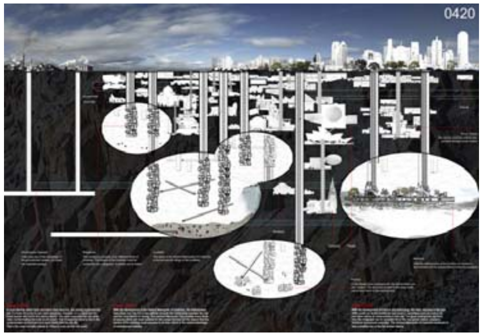
Residential

Humid subtropical (Cfa)

Below ground level	**≈ 100%**
Surface to ground	**≈ 100%**
Depth	**≈ 500m**

- China extracts an average of 2 billion tons of coal each year to satisfy its energy demands. Apart from the environmental concerns, coal mining is an extremely dangerous profession which leads to more than 6000 deaths every year.
- The main concept behind this proposal is to make use of the immense coal mines as an underground city where miners will have access to a better quality of life through modern housing and recreational areas. This underground metropolis will coexist with regular cities and will integrate them through an exchange of goods and services.





\# http://www.evolo.us/architecture/underground-metropolis/

Yaodong (窰洞) "Cave House"

23

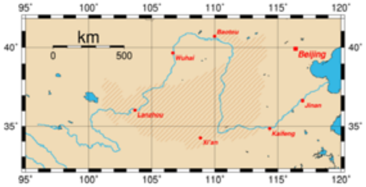
Loess Plateau, Shaanxi province, China| from the Han dynasty 206 B.C.

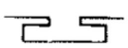
Residential

Humid subtropical (Cfa)

Below ground level	**≈ 100%**
Surface to ground	**≈ 60%**
Depth	**≈ 8m**

- Generally carved out of a hillside or excavated horizontally from a central "sunken courtyard"
- Little building material is needed, which is scarce in the loess plateau.
- An estimated 40 million people in northern China live in Yaodongs.





\# http://chinablog.cc/2009/02/yaodong-cave-dwellings-on-loess-plateau/
\# http://en.wikipedia.org/wiki/Yaodong

Glass Temple

24

Takashi Yamaguchi | Kyoto, Japan | 1998

Religious

Humid subtropical (Cfa)

- To maintain the integrity of the historic building, the new temple was placed underground, if not rendered entirely invisible.

Below ground level	**≈ 80%**
Surface to ground	**≈ 70%**
Depth	**≈ 6m**

E. von Meijenfeldt, Below Ground Level, 2003
http://www.architizer.com/en_us/blog/dyn/21616/a-necessary-courtesy-the-glass-temple/

Alice city (idea)

25

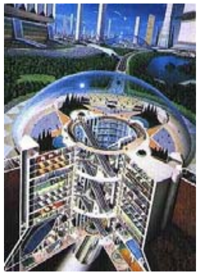
Taisei Corporation | Tokyo, Japan

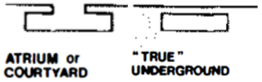
Residential, Office, Infrastructure, Education

Humid subtropical (Cfa)

- In their infrastructure areas, they plan power generation, regional heating, waste recycling and sewage treatment facilities. As shown in the accompanying pictures such underground space can be spherical or cylinder-shaped.
- Construction costs have been studied in considerable depth, a 12floor office space (80m deep) would cost about €440 million and a 80-m diameter and 60m high infrastructure space placed on 110 m underground would run about €530 million. Total cost for a city of 100,000 is estimated at €3 billion, roughly half the price of one high-priced surface acre on Tokyo's Ginza strip!

Below ground level	**≈ 80%**
Surface to ground	**≈ 70%**
Depth	**≈ 100m**





http://www.drtomorrow.com/lessons/lessons7/20.html
http://www.zey.com/Featured_2.htm

Apple Store

26

Bohlin Cywinski Jackson | New York, U.S.A.| 2010

Retail

Humid subtropical
(Cfa)

Below ground level	≈ 80%
Surface to ground	≈ 80%
Depth	≈ 5m

\# http://www.apple.com/retail/fifthavenue/gallery/gallery4.html
\# http://intransit.blogs.nytimes.com/2010/04/01/apple-store-most-photographed-in-new-york/

Chichu Art Museum

27

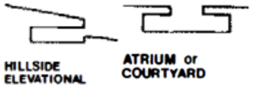
Tadao Ando | Naoshima, Kagawa Prefecture, Japan | 2004

Leisure

Humid subtropical
(Cfa)

- To ensure that the museum does not affect the beautiful scenery of Naoshima, the majority of the building is located underground. Despite its positioning, it receives an abundance of natural light, changing the appearance of the artworks and the ambience of the space itself with the passage of the days and the seasons.

Below ground level	≈ 100%
Surface to ground	≈ 70%
Depth	≈ 10m



\# http://www.benesse-artsite.jp/en/chichu/index.html
\# http://www.vuw.ac.nz/architecture-onlineteaching/courses/arch403/assign1/matthew_colson_chichu.pdf

Water Temple

28

Tadao Ando | Tsuna-gun, Hyogo, Japan | 1991

Religious

Humid subtropical (Cfa)

≤ The roof of the building consist of a pool, which has different thermal properties than an earth covered roof.

≥ Surprisingly, the lotus pool is actually the roof of the temple, which is built partly underground; to reach the sanctuary visitors descend a stairway which cuts the oval shape of the pool in two.

Below ground level	**≈ 40%**
Surface to ground	**≈ 50%**
Depth	**≈ 7m**

\# Barker, M., 1986. Using the Earth to Save Energy: Four Underground Buildings. Tunneling and Underground Space Technology

\# http://michiganmodern.org/architects-designers-firms/architects/gunnar-birkerts/

Prefectural International Hall

29

Emilio Ambasz | Fukuoka, Japan | 1994

Leisure, Office, Retail, Storage

Humid subtropical (Cfa)

≥ Underneath the park's fifteen one-story terraces lies over one million square feet of multipurpose space containing an exhibition hall, a museum, a 2000-seat proscenium theater, conference facilities, governmental and private offices, as well as several underground levels of parking and retail space

Below ground level	**≈ 30%**
Surface to ground	**≈ 30%**
Depth	**≈ 12m**

\# http://www.greenroofs.com/projects/pview.php?id=476

\# http://www.archidose.org/Dec00/121100.html

NLE Museum

30

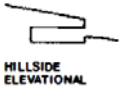
Davis Buckley Architects and Planners| Washington, DC, U.S.A. | Concept

Leisure

Humid subtropical
(Cfa)

- Two glass garden-like pavilions invite visitors in to the museum and fill the space below with natural light. Glass pavers set within the stone plaza and between the pavilions create a varied pattern of light on the ceiling of the main atrium.
- However there is no room for it to fit nicely into the square! At least, above ground. Davis Buckley's proposal for the Museum is for two 4,000-square foot, above-ground glass-entry pavilions. These are supposed to symbolize the visibility of law enforcement but also provide an unobtrusive entrance on the historic square.

Below ground level	**≈ 70%**
Surface to ground	**≈ 70%**
Depth	**≈ 4m**



\# http://www.homedesignfind.com/green/10000-square-foot-underground-bunker-will-remain-forever/

\# http://www.longhiarchitect.com/home.html

Shanghai Cultural Plaza

31

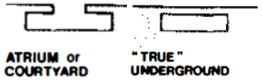
Beyer Blinder Belle Architects | Shanghai, China | 2011

Leisure

Humid subtropical
(Cfa)

- The lobby is lit only by sunshine; in the evenings, artist Ding Shaoguang's massive blue-green rainforest painting will glow with LED light, echoing the stained-glass windows of European cathedrals. Better still, the building plunges 26 meters underground, providing natural heating and air conditioning while cutting both its costs and carbon footprint.

Below ground level	**≈ 80%**
Surface to ground	**≈ 80%**
Depth	**≈ 30m**



\# http://www.beyerblinderbelle.com/?ID=196

Springfield Underground

32

- | Springfield, Missouri, U.S.A. | -

Storage

Humid subtropical (Cfa)

- Going underground is an environmentally friendly business decision without the added cost of an aboveground green facility. Because Springfield Underground is 100 feet below the surface, it is below the weather. There is no seasonal temperature variation, meaning that you spend a smaller, more uniform amount on utilities. And there are no worries about weather-related catastrophes the way aboveground facilities do.

Below ground level	**≈ 100%**
Surface to ground	**≈ 100%**
Depth	**≈ 30m**

\# http://www.springfieldunderground.com/

Canary Wharf tube station

33

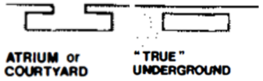
Norman Foster | London, United Kingdom | 1999

Infrastructure, Retail

Maritime temperature (Cfb)

- The main reason for the station's enormous dimensions was the great number of passengers predicted; as many as 50.000 daily. These predictions have outgrown, with as many as 70.000+ today.
- Above ground there is little sign of the vast interior: two curved glass canopies at the east and west ends of the station cover the entrances and allow daylight into the ticket hall below. A public park is situated between the two canopies, above the station concourse.

Below ground level	**≈ 100%**
Surface to ground	**≈ 90%**
Depth	**≈ 25m**



\# http://www.greenroofs.com/archives/sg_jan-apr04.htm

\# http://en.wikipedia.org/wiki/Canary_Wharf_tube_station

London Hotel (concept)

34

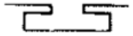
Reardon Smith Architects | Surrey, London, United Kingdom| Concept

Residential

Maritime temperature (Cfb)

- In addition to the green integrated into the building, the proposal includes the addition of extensive on-site re-vegetation and re-organization of existing spaces (such as parking) that will actually leave the site even more eco-friendly than it is now.

Below ground level ≈ 90%
Surface to ground ≈ 70%
Depth ≈ 10m



ATRIUM or COURTYARD

http://inhabitat.com/5-star-underground-hotel-in-london/

Woodland Home

35

Reardon Smith Architects | Surrey, London, UK | ?

Residential

Maritime temperature (Cfb)

- Fridge is cooled by air coming underground through foundations.
- Skylight in roof lets in natural feeling light.
- Solar panels for lighting, music and computing.

Below ground level ≈ 0%
Surface to ground ≈ 60%
Depth ≈ 0m

BERM ELEVATIONAL

http://www.simondale.net/house/

Steel dome

36

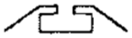
Bill Lishman | Purple Hill, UK | 1988

Residential

Maritime temperature (Cfb)

- "To pursue building a house such as this the costs are higher than building conventionally because it involves moving tons of earth and a great deal of work by skilled artisans. The costs will be recouped during the life of the house and in the long run it will be cheaper and more rewarding but the initial building takes a great deal of dedication".

Below ground level	**≈ 0%**
Surface to ground	**≈ 90%**
Depth	**≈ 3m**



ATRIUM or COURTYARD

http://www.williamlishman.com/underground.htm

The Shire (fictional)

37

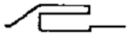
J.R.R. Tolkien | New Zealand

Residential

Maritime temperature (Cfb)

- A fictional place where earth-sheltered homes are build to house "Hobbits" in the Lord of the Rings trilogy.

Below ground level	**≈ 0%**
Surface to ground	**≈ 90%**
Depth	**≈ 3m**



BERM ELEVATIONAL

http://students.english.ilstu.edu/rwohara/creation/shire.html

Fac. Dans en Theater ArtEZ

38

Henket & Partners architecten| Arnhem, Gelderland | 2004

Educational

Maritime temperature (Cfb)

- Application of special sun blocking cloths between trusses, to spread incoming light. The cloths are made of plasticized glass fiber.
- For fire safety use is made of windows that open during a fire to release smoke and heat out of the building, to create a smokefree environment for easier evacuation.
- Ventilation grids of 1.2m in height are applied in the glass facades to release daily heat.
- Lowest floor at 10m depth.

Below ground level	**≈ 100%**
Surface to ground	**≈ 80%**
Depth	**≈ 10m**

http://www.abt.eu/nl/projecten.asp?projectcatid=4&projectid=68

UNESCO House site

39

Marcel Breuer, Piero Nervi and Bernard Zehrfuss | Paris, France | -

Office, Leisure

Maritime temperature (Cfb)

- One of the three buildings that completes the headquarters site of the UNESCO House in Paris, consisting of two office floors hollowed out below street level, around six small sunken courtyards, containing many remarkable works of art and are open to the public.

Below ground level	**≈ 100%**
Surface to ground	**≈ 70%**
Depth	**≈ 6m**

http://www.unesco.org/new/en/unesco/about-us/who-we-are/history/paris-headquarters/
http://us.franceguide.com/UNESCO-IN-FRANCE.html?NodeID=1&EditoID=83582

Le Carrousel Du Louvre

40

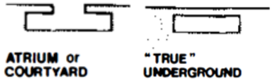
I.M. Pei, Macary, Duval | Paris, France | 1993

Leisure

Maritime temperature (Cfb)

Below ground level	**≈ 100%**
Surface to ground	**≈ 80%**
Depth	**≈ 10m**

- Roughly at midpoint, the avenue is interrupted by a small upside-down glass pyramid, a witty reminder of its famous aboveground counterpart. On sunny days, it reflects all the colors of the rainbow.
- Certain measures create the feeling of being outside: the lighting generates a kind of accelerated perspective, making the space seem even higher and lighter, while the ventilation has been designed to produce an occasional breeze, and even noticeable changes in temperature.



\# E. von Meijenfeldt, Below Ground Level, 2003
\# http://www.atkielski.com/PhotoGallery/Paris/Louvre/InvertedPyramidSmall.html

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Great Glass House

41

Foster + Partners | Carmarthenshire, U.K. | 2000

Educational, Retail, Leisure

Maritime temperature (Cfb)

Below ground level	**≈ 70%**
Surface to ground	**≈ 50%**
Depth	**≈ 6m**

- The buildings concrete substructure is banked to the north to provide protection from cold northerly winds and is concealed by a covering of turf so that the three entrances on the northern side appear to be cut discreetly into the hillside. Within this base are a public concourse, a café, educational spaces and service installation.
- To optimize energy usage, conditions inside and outside are monitored by a computer-controlled system. This adjusts the supply of heat and opens glazing panels in the roof to achieve desired levels of temperature, humidity and air movement.
- The principal heat source is a biomass boiler, located in the parks Energy Centre, which burns timber trimmings. This method is remarkably clean when compared with fossil fuels.
- Rainwater collected from the roof supplies grey water for irrigation and flushing lavatories while waste from the lavatories is treated in reed beds before release into a watercourse.

\# E. von Meijenfeldt, Below Ground Level, 2003
\# http://www.fosterandpartners.com/Projects/0861/Default.aspx

Bolton Eco House (Concept)

42

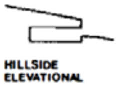
Make Architects | North West England, UK | 2009

Residential

Maritime temperature (Cfb)

- The four-bedroom, single-storey family home is deliberately embedded into the contours of the Pennine hillside to minimize the impact on the surrounding moorland and has a roof of flora and meadow grasses which flows seamlessly over the property and into the landscape.
- It has been designed to consume less energy than it uses; a ground source heat pump, photovoltaic panels and a wind turbine will generate on-site renewable energy.

Below ground level	**≈ 80%**
Surface to ground	**≈ 70%**
Depth	**≈ 3m**



\# http://www.makearchitects.com/#/projects/9067/
\# http://dornob.com/uk-celebrity-plans-on-building-huge-underground-eco-home/

Hills Homes (Concept)

43

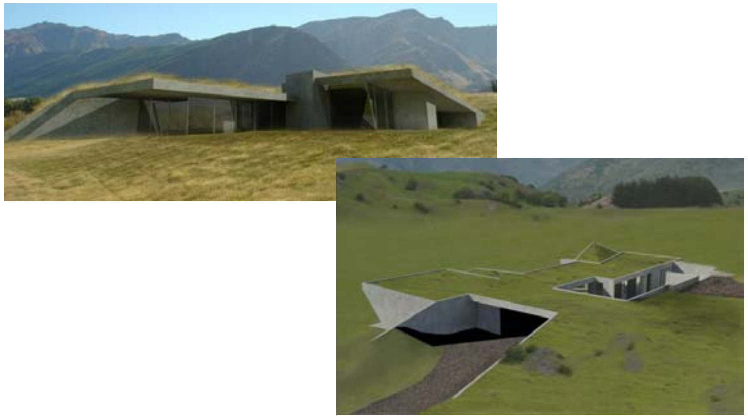
Pattersons | Arrowtown, New Zealand | 2007

Residential

Maritime temperature (Cfb)

- Each home will be between 367 and 700 square meters, with turf and pebble roofs.
- Kiwi tycoon Michael Hill wanted to build homes on and around his golf course, but he didn't want them to interfere with the views of the area.

Below ground level	**≈ 40%**
Surface to ground	**≈ 40%**
Depth	**≈ 3m**



\# http://www.pattersons.com/

RAF Holmpton

44

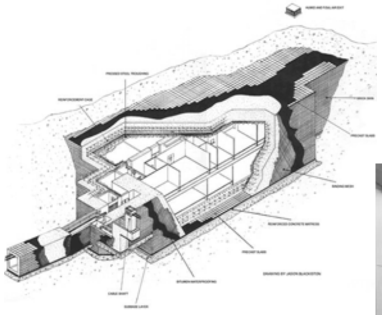
- | Holmpton, U.K. | 1954

Military

Maritime temperature (Cfb)

- On top of this the bunker was provided with two floors accounting for an internal height of 22ft. Above this a steel shuttered fabrication to form the ceiling and then the outer shell of 10ft of concrete.

Below ground level	**≈ 100%**
Surface to ground	**≈ 100%**
Depth	**≈ 30m**



"TRUE" UNDERGROUND

http://www.subbrit.org.uk/rsg/sites/h/holmpton/

Malator

45

Future Systems | Druidston, Pembrokeshire, U.K.| 1998

Residential

Maritime temperature (Cfb)

- The basic design of Malator is very simple, with essentially one room inside, divided by prefabricated colored pods, while on the outside the house melds with the surrounding landscape.

Below ground level	**≈ 80%**
Surface to ground	**≈ 85%**
Depth	**≈ 3m**

BERM ELEVATIONAL

http://en.wikipedia.org/wiki/Malator
http://www.s4c.co.uk/tycymreig/e_p8main.shtml

The underground house

46

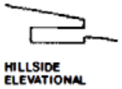
2030 Architects |Appleby, Cumbria, U.K. | ~2010

Residential

Maritime temperature (Cfb)

- Cumbria's first earth-sheltered dwelling and the subject of a Channel Four "Grand Designs" programme, demonstrated how such construction methods can achieve a light and airy, zero heat dwelling for a similar cost to that of more conventional buildings. A simple mechanical ventilation and heat recovery system, powered in part by a small photovoltaic array aided by a 6kw wind turbine, provides a healthy interior environment.

Below ground level	**≈ 0%**
Surface to ground	**≈ 30%**
Depth	**≈ 5m**



\# http://www.2030architects.co.uk/#!residential/c20x9

\# http://www.youtube.com/watch?v=lnD7OD2svbI&feature=player_embedded

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Phillip Island House

47

Denton Corker Marshall| Phillip Island, Victoria, Australia| 1989

Residential

Maritime temperature (Cfb)

- Buried into the dunes, the house is visible from the beach as a low black line – the colour of the rocks – with ragged tufts of dune grass above it. It is completely hidden from the landward side. The objective was to maintain a low profile and to have an internal focus to the house, avoiding engagement with the surrounding context.
- The house is a long thin concrete box, black inside and outside, set along one edge of a large square courtyard contained by three metre high black concrete walls with dune berms ramped up to roof level on three sides. On the open ocean elevation, windows are sized and positioned within each room to act as picture frames to the views, and the proportions and locations of the windows are determined by these internal considerations. The courtyard offers protection from winds and is a north facing sun trap in winter.

Below ground level	**≈ 40%**
Surface to ground	**≈ 60%**
Depth	**≈ 3m**

\# http://www.architonic.com/aisht/marshall-house-denton-corker-marshall/5100501

\# http://www.dentoncorkermarshall.com/projects/phillip-island-house/

Mile End Park

48

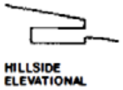
Gardner Stewart Architects | London, U.K. | 2001

Leisure, Retail

Maritime temperature (Cfb)

Below ground level	**≈ 80%**
Surface to ground	**≈ 50%**
Depth	**≈ 3m**

- At an architectural level, these Passive Annual Heat Storage buildings are amongst the most ecologically responsible in the country and have been designed to minimise the demand on all natural resources. They have the following key environmental attributes:
- No heat input requirement means a corresponding dramatic reduction in emissions. Boreholes provide entire water requirements, including lakes, irrigation & buildings
- Thermal stability across the year, due to entire building acting as heat sump
- Low-tech a/c with air naturally cooled & filtered by series of underground pipes
- Virtually maintenance free beyond cleaning requirements
- Promotion of immense wealth of biodiversity in both the park and buildings.



\# http://inhabitat.com/spiky-ecology-pavilion-sprouts-in-east-london/\

\# http://www.gardnerstewartarchitects.com/portfoliomenu/portfoliomenu.htm

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Earth Sheltered House

49

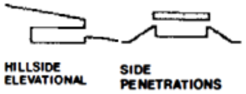
LOM | Devon, U.K. | 2010 (Concept)

Residential

Maritime temperature (Cfb)

Below ground level	**≈ 50%**
Surface to ground	**≈ 65%**
Depth	**≈ 1-6m**

- An innovative 3,500 ft² low carbon home in the Devon countryside, designed to offer best practice in environmental sustainability. The site is located close to an area of outstanding natural beauty, and the house is built into a hillside to reduce visual impact and provide a high level of insulation.
- The building uses a green roof, a triple glazed primary facade with solar shading, geothermal and waste air heat reclamation, rainwater storage and grey water recycling systems.



\# http://www.lom-fdp.com/lom/portfolio/private-client-earth-sheltered-house/

Icelandic turf houses

50

- | Saenautasel / Glaumbaer, Iceland| 10th Century

Residential

Subarctic (Dsc)

- The Icelandic turf house was the product of a difficult climate, offering superior insulation compared to buildings solely made of wood or stone, and the relative difficulty in obtaining other construction materials in sufficient quantities.
- The floor of a turf house could be covered with wood, stone or earth depending on the purpose of the building. They contain grass on their roofs.

Below ground level ≈ 0%
Surface to ground ≈ 60%
Depth ≈ 0m





http://en.wikipedia.org/wiki/Icelandic_turf_houses

COEX mall

51

- | Samseong-dong , Gangnam-gu area of Seoul, South Korea |-

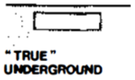
Retail, Infrastructure, Office, Recreation

Hot Summer Continental (Dwa)

- Asia's largest underground shopping mall with an area of about 85,000m^2.
- In it resides hundreds of shops, the mall houses two food courts, a 16-screen multi-cinema complex, an aquarium attraction, a large bookstore, and the Kimchi Field Museum

Below ground level ≈ 80%
Surface to ground ≈ 40%
Depth ≈ 15m



http://www.lifeinkorea.com/travel2//215
http://www.coexmall.com/eng/index.asp

Earth House

52

Byoungsoo Cho | Yangpyeong-gun, Gyeonggi-do, Republic of Korea | 2009

Residential

Hot Summer Continental (Dwa)

- The house uses a geothermal cooling system with a radiant floor heating system under the rammed clay and concrete floor. Off-peak electricity is used at night to heat the small gravel under the floor.
- A combination of passive cooling and geothermal tubes which are buried in the earth around the buildings keep the temperature cool in summer and warm in winter.

Below ground level	**≈ 100%**
Surface to ground	**≈ 70%**
Depth	**≈ 3m**

http://www.archdaily.com/73831/earth-house-bcho-architects/
http://inhabitat.com/soeul-gains-an-underground-house-by-byoung-soo-cho/tub2/

The Civil Engineering Building

53

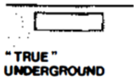
BWBR Architects, Inc. | University of Minnesota, Minneapolis, U.S.A.| 1983

Educational

Warm Summer contintental (Dwb)

- Earth-sheltered building 95% underground
- Winner 1983 ASCE Outstanding Civil Engineering Achievement Award.

Below ground level	**≈ 40%**
Surface to ground	**≈ 50%**
Depth	**≈ 21m**



Barker, M., 1986. Using the Earth to Save Energy: Four Underground Buildings. Tunneling and Underground Space Technology
http://www.mbjeng.com/home/projects/education/umn-civil-engineering

Cottages at Fallingwater

54

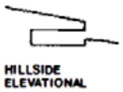
Patkau Architects | Fallingwater, Pennysylvania, U.S.A.| 2010 -

Residential

Hot Summer Continental (Dfa)

Below ground level	**≈ 90%**
Surface to ground	**≈ 90%**
Depth	**≈ 3m**

- Patkau Architects won a competition run by the Western Pennsylvania Conservancy, an institute that looks after the preservation and maintenance of Fallingwater.
- The six new units will serve as accommodation for participants in the institute's further-education programme.
- The jury praised the subtle, yet progressive, character of the design, with its minimal impact on the landscape, which also met the criteria of sustainability and energy efficiency that had been set down.



\# http://www.architonic.com/ntsht/camouflage-architecture-underground-buildings/7000497

\# http://www.patkau.ca/

SubTropolis

55

Mined space | Kansas City, Missouri, U.S.A. | 1940s

Industrial, Storage, Office

Hot Summer Continental (Dfa)

Below ground level	**≈ 100%**
Surface to ground	**≈ 98%**
Depth	**≈ ?m**

- 5.060.000 m³, 4.5km² manmade mines, claimed to be the world's largest underground storage facility.
- Currently 460,000 m³ is occupied and 920,000 m³ are "improved." About 13,000 m² of available space are added each year as active mining continues.
- The mine naturally maintains temperatures between 18 to 20˚C year-round.
- Fully sprinkler installed
- Constant relative humidity levels.

\# http://en.wikipedia.org/wiki/SubTropolis

\# http://www.huntmidwest.com/subtropolis/movies/overview.html

PATH Shopping complex

56

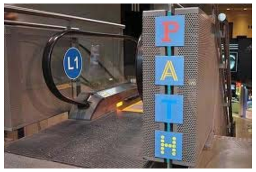
- |Toronto, Ontario, Canada | from 1900

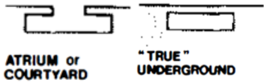
Retail, Infrastructure, Office, Recreation

Hot Summer Continental (Dfa)

- PATH is the largest underground shopping complex in the world with 371,600 m² of retail space.
- More than 50 buildings/office towers are connected through PATH. Twenty parking garages, five subway stations, two major department stores, six major hotels, and a railway terminal are also accessible through PATH.

Below ground level ≈ 80%
Surface to ground ≈ 70%
Depth ≈ 30m





\# http://www.toronto.ca/path/
\# http://en.wikipedia.org/wiki/PATH_%28Toronto%29

Soft and Hairy House

57

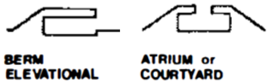
Ushida-Findlay Partnership | Tokyo, Japan | 1994

Residential

Hot Summer Continental (Dfa)

- The more intimate rooms are enveloped as though within protective capsules, while the house itself folds around an inner courtyard. The height of surrealism is its blue, egg-shaped bathroom, which is at the home's center.

Below ground level ≈ 0%
Surface to ground ≈ 40%
Depth ≈ 3m



\# E. von Meijenfeldt, Below Ground Level, 2003
\# http://www.ushida-findlay.com/project/soft-and-hairy-house/

Huge cave house

58

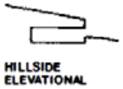
- | Festus, Missouri, U.S.A.| -

Residential

Hot Summer Continental (Dfa)

- This enormous mansion was made in an existing cave in the small town of Festus, Missouri. Before it was a private residence, the cave was used as a concert hall and a skating rink, among other things.

Below ground level ≈ 0%
Surface to ground ≈ 80%
Depth ≈ 0m



http://webecoist.momtastic.com/2010/01/20/going-green-underground-16-subterranean-eco-buildings/9-huge-cave-home-missouri/

Joe and Rika Mansueto library

59

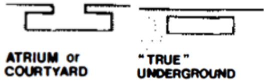
Helmut Jahn| Chicago, U.S.A. | 2008

Educational

Hot Summer Continental (Dfa)

- The Mansueto Library houses cutting-edge facilities for the preservation and digitization of physical books, as well as a high-density underground storage system with the capacity to hold 3.5 million volume equivalents.

Below ground level ≈ 60%
Surface to ground ≈ 65%
Depth ≈ 10m



http://www.architonic.com/ntsht/underground-structures/7000652
http://www.murphyjahn.com/projects

Itäkeskus swimming pool

Hyvamaki-Karhunen Parkkinen | Itäkeskus, Helsinki, Finland | 1993

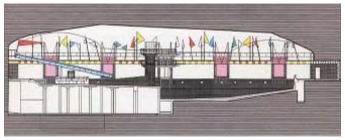
60

Hemiboreal (Dfb)

Recreational

- The entire complex is built within the rocks, and the interior reflects the contours of the exterior rocks.
- It is made for 1.000 visitors and can be used as a bomb shelter for 3.800 people.

Below ground level	**≈ 100%**
Surface to ground	**≈ 98%**
Depth	**≈ ?m**



http://www.hkp.fi/
http://www.getunderground.fi/web/printpreview.aspx?printpreview=1&refid=148

Temppeliaukio Church

Timo and Tuomo Suomalainen | Etu-Töölö, Helsinki, Finland | 1969

61

Hemiboreal (Dfb)

Religious

- The interior is excavated an built into the rock, but is bathed in natural light entering through the glazed dome.
- The church is frequently used as a concert venue due to its excellent acoustics which are ensured by the rough, virtually unworked rock surfaces.

Below ground level	**≈ 70%**
Surface to ground	**≈ 30%**
Depth	**≈ 5m**

http://en.wikipedia.org/wiki/Temppeliaukio_Church
http://www.muuka.com/finnishpumpkin/churches/helsinki/chteh/church_chteh.html

Legal Research Building

62

Gunnar Birkert | Ann Arbor, Michigan, U.S.A. | 1982

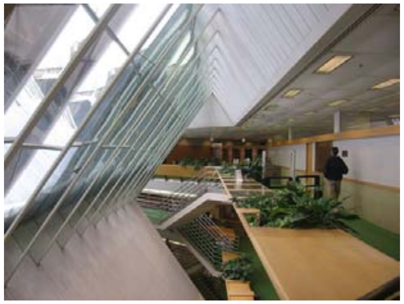
Educational

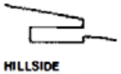
Hemiboreal (Dfb)

Below ground level	**≈ 50%**
Surface to ground	**≈ 50%**
Depth	**≈ 15m**

≤ The energy performance of this building has not been superior to an above-grade building structure of the same size built for the same purpose

≥ The legal research building for the University of Michigan is designed to protect the existing gothic revival buildings and courtyards.





HILLSIDE ELEVATIONAL

ATRIUM or COURTYARD

\# Barker, M., 1986. Using the Earth to Save Energy: Four Underground Buildings. Tunneling and Underground Space Technology

\# http://michiganmodern.org/architects-designers-firms/architects/gunnar-birkerts/

Wieliczka Salt Mine

63

- | Wieliczka, Poland| 13th century

Leisure (Tourism)

Hemiboreal (Dfb)

Below ground level	**≈ 100%**
Surface to ground	**≈ 100%**
Depth	**≈ 327m**

≥ Several hundreds of years of rock salt exploitation have shaped the spatial arrangement of its excavated structure. Lying on nine levels, concealed under the town, the mine reaches down to the depth of 327 metres. Subterranean Wieliczka consists of nearly 300 kilometres of corridors and almost 3,000 chambers. The tourist route accessible to visitors includes a 3.5-kilometres section located from 64 to 135 metres below ground level.

≥ The Wieliczka mine functions also as a sanatorium, for the micro-climate in the underground spaces is particularly beneficial in the treatment of upper respiratory disorders, asthma and allergy. In 1997 the Underground Rehabilitation and Medical Centre was opened. Owing to the active therapy in the Centre, the patients breathe in the air rich in sodium, calcium and magnesium chloride, and thus efficiently get rid of some disorders caused by civilization.

"TRUE" UNDERGROUND

\# http://www.hotelraider.com/salt-mine-wieliczka/

Ecology House

64

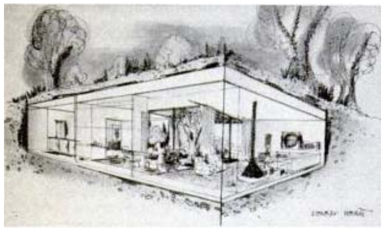
John E. Barnard Jr. | Marstons Milss, Massachusetts, U.S.A. | 1972

Residential

Hemiboreal (Dfb)

- One-fifth normal heating cost, 25% lower building cost, privacy from neighbors and no unsightly damage to surrounding property

Below ground level ≈ 100%
Surface to ground ≈ 80%
Depth ≈ 4m



\# http://we-make-money-not-art.com/archives/2009/08/sorry-out-of-gas-architectures.php
\# Popular Mechanics, June 1974

Vacation house

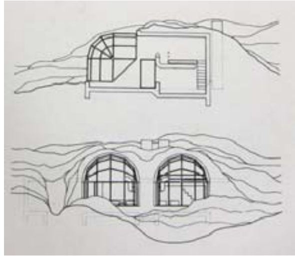
65

Claus Bonderup | Jutland, Denmark | ~1970

Residential

Hemiboreal (Dfb)

Below ground level ≈ 50%
Surface to ground ≈ 80%
Depth ≈ 3m



\# http://newspirit-square1.blogspot.com/2010/06/claus-bonderups-vacation-house.html

“Salzburg Guggenheim” (Idea)

66

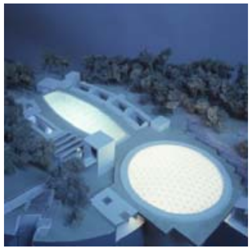
Hans hollein | Salzburg, Austria | 1989 (concept)

Leisure

Hemiboreal (Dfb)

- 1989 Hans Hollein’s project was the winner of an international invited competition for a museum in the Mönchsberg—a large rock formation that is one of the principal features in the city of Salzburg. The singular feature of his design is the fact that the proposed museum is enclosed entirely within the volume of the Mönchsberg rock on three levels. It has no visible façade. The gallery spaces on the upper two levels are covered by a vast system of skylights that offer light to the subterranean museum. Building inside the rock allows free, a–tectonic expansion in all directions. The project was continued as a feasibility study for a “Salzburg Guggenheim” and, after optimizing the program in a transformed, reduced condition, was being discussed as a location for cooperation between Kunsthistorisches Museum, Wien, Guggenheim Museum, New York and Eremitage, Sankt Petersburg.

Below ground level	**≈ 95%**
Surface to ground	**≈ 90%**
Depth	**≈ 50m**



“TRUE” UNDERGROUND

http://www.subbrit.org.uk/rsg/sites/h/holmpton/

Underground data center

67

- | Pionen, Stockholm, Sweden | 2008

Storage

Hemiboreal (Dfb)

- Originally a nuclear bunker: The data center is housed in what was originally a military bunker and nuclear shelter during the Cold War era. The facility still has the code name from its military days: Pionen White Mountains.
- Located in central Stockholm below 30 meters (almost 100 ft) of bedrock: The facility has 1110 sqm (11950 sq ft) of space and is located below 30 meters of solid bedrock (granite) right inside the city.
- 1.5 megawatt of cooling for the servers: Cooling is handled by Baltimore Aircoil fans producing a cooling effect of 1.5 megawatt, enough for several hundred rack-mounted units.
- Work environment with simulated daylight and greenhouses: For a pleasant working environment the data center has simulated daylight, greenhouses, waterfalls and a huge 2600-liter salt water fish tank.

Below ground level	**≈ 100%**
Surface to ground	**≈ 100%**
Depth	**≈ 30m**

“TRUE” UNDERGROUND

http://royal.pingdom.com/2008/11/14/the-worlds-most-super-designed-data-center-fit-for-a-james-bond-villain/

http://abdtechnology.com/our-company/data-centers/swedish-facility-pionen-stockholm-sweden/

RÉSO or La Ville Souterraine

68

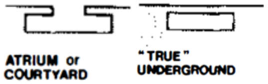
Montreal, Quebec , Canada| from 1962

Retail, Infrastructure, Office, Leisure, Education

Subartic
(Dfc)

- With over 32 km of tunnels spread over more than 12 km^2 , connected areas include shopping malls, apartment buildings, hotels, condominiums, banks, offices, museums, universities, seven metro stations, two commuter train stations, a regional bus terminal and the Bell Centre amphitheater and arena.

Below ground level	**≈ 80%**
Surface to ground	**≈ 70%**
Depth	**≈ 30m**



http://en.wikipedia.org/wiki/Underground_city,_Montreal
http://www.montreal.com/top/

Nine Houses

69

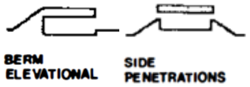
Peter Vetsch | Dietikon, Switzerland | 1993

Residential

Tundra
(ET)

- The organic construction consists of shotcrete, with a 25 cm layer of polymer bitumen and recycled glass foam on top.
- Access to the houses is at the sides, entirely out of sight to the benefit of their free forms.
- Interior room such as kitchens and bathrooms are illuminated by domed skylights.

Below ground level	**≈ 0%**
Surface to ground	**≈ 40%**
Depth	**≈ 0m**



E. von Meijenfeldt, Below Ground Level, 2003
http://www.greenroofs.com/projects/pview.php?id=354

Maison sous-terraine

70

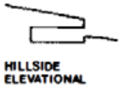
SeARCH & Christian Müller Architect | Vals, Switzerland | 2008

Residential

Tundra (ET)

- The introduction of a central patio into the steep incline creates a large façade with considerable potential for window openings.
- The viewing angle from the building is slightly inclined, giving an even more dramatic view of the strikingly beautiful mountains on the opposite side of the narrow valley.

Below ground level	**≈ 100%**
Surface to ground	**≈ 70%**
Depth	**5m**



\# http://www.youtube.com/watch?v=u7CWjtM1938
\# http://www.treehugger.com/sustainable-product-design/underground-houses-vals-house-by-search-and-christian-ma14ller-architects.html
\# http://www.christian-muller.com/CMA_Projects-HVV.html

Gjøvik Olympic Cavern Hall

71

Moe-Levorsen | Gjøvik, Oppland, Norway | 1993

Leisure

Tundra (ET)

- World's largest cavern hall for public use.
- An ice hockey rink located within a mountain hall, with a capacity for 5,500 spectators, the hall also features a 25-meter swimming pool and telecommunications installations.

Below ground level	**≈ 100%**
Surface to ground	**≈ 98%**
Depth	**≈ ?m**

\# http://en.wikipedia.org/wiki/Gj%C3%B8vik_Olympic_Cavern_Hall
\# http://www.fjellhallen.no/gammel/engindex.html