Evaluation Of Building Energy Performance: Comparison Before And After Envelope Retrofitting

Ali Derai[1], Monika WOLOSZYN[1], Amandine PIOT[2] and Lamia BERRAH[3]

[1] Univ. Savoie Mont Blanc, Solar Academy Graduate School, LOCIE, Chambéry, F-73000

[2] Univ. Grenoble Alpes, CEA, Liten, Campus Ines, 73375 Le Bourget du Lac, France

[3] Univ. Savoie Mont Blanc, LISTIC, Annecy-le-Vieux, France

Abstract

Both governments and scientific communities across the world have identified the potential and need for energy efficiency in buildings and have initiated significant efforts in this direction. The energy performance could be improved by adding envelope insulation and exploiting the energy resources that come from the surroundings. To succeed in this process, the evaluation of building performance and energy resource quality is necessary. Different configurations of a single-family house (INCAS Building) will be evaluated and compared in this article. To determine the most effective configuration for optimizing the building envelope, as well as to explore the effect of insulation on the bioclimatic performance of the building. This study examines a building's performance using a new set of indicators developed from earlier research. The results of the analyses will be used to better understand those indicators and improve their use; and finally, this study will serve as the first step toward developing a new building evaluation method.

Keywords: energy efficiency, insulations, solar resources, performance indicators, buildings envelopes.

1. Introduction

Building energy consumption has increased to a level that exceeds that of other key sectors (industry and transportation), due to population growth, improvements in comfort and building services, as well as an increase in the amount of time people spend within buildings. This fact highlights the crucial need for energy savings in buildings. Today, both governments and scientific communities believe that focusing on buildings is essential to reducing energy consumption and carbon emissions. Almost 75% of the EU building stock was built before the introduction of the first building codes in the 1970s. Those existing buildings constitute, therefore, the greatest opportunity for energy efficiency improvements. The buildings we find today are expected to achieve both energy-efficient and environmental-friendly designs. The concept of sustainable buildings includes several challenges relating to environmental pollution, interior and outdoor air quality, energy, water, land, and material conservation. Active or passive energy-efficient measures can be used to increase a building's energy efficiency. HVAC system upgrades, electrical lighting upgrades, etc. may all be considered active techniques, whilst building envelope element upgrades fall under the category of passive strategies. Recently, there has been a renewed interest in passive building energy efficiency techniques. They are considered to be an effective solution to the issues of the energy crisis and environmental pollution (Sadineni et al., 2011). The effort to improve the envelope’s energy performance can be divided into two types. The first type consists of thermal insulation to prevent heat exchange with the exterior of the building. The second way is by improving the building capacity to exploit more energy from its surrounding, by applying passive strategies. Such approach is called bioclimatic architecture.

Following this introduction, the next sections of this paper provide a brief literature review on the topic of bioclimatic architecture and passive technologies, followed by a presentation of the various indicators that will be employed in the study. After that comes the methodology, which contains a description of the building and simulation configurations. Then, the next section describes the simulation results and the different indicators graphs. Finally, the paper is closed with the main conclusions of the study presented in Section 6.

doi:10.18086/eurosun.2022.02.03 Available at http://proceedings.ises.org

2. Brief literature review

The aim of architecture has always been to shelter man from the outer environment, architectural evolutions have happened throughout history and in every region and climate to reach the best comfort levels in interior spaces. In this situation, bioclimatic architecture strives to accomplish human thermal comfort by engaging energetically with the exterior climate (Manzano-Agugliaro et al., 2015). The bioclimatic architecture term refers to the technique of construction that considers local climate conditions. It employs appropriate technologies and design principles based on a reflexive focus on the climate and environment to increase energy efficiency. Passive strategies are constructive technologies integrated within buildings, the main objective and function of these solutions are to contribute to the natural cooling or heating of the building and to minimize the building energy needs. These methods are the oldest way to reduce heating and cooling loads in buildings. When dimensioned correctly, they can significantly reduce a household's energy consumption (Bajcinovci & Jerliu, 2016; Budescu, 2013; Ness, 2017).

Passive strategies could be classified as heating and cooling strategies. Passive heating solutions are built into building structures or housings and can act as collectors and accumulators of incidental solar energy, without using active air conditioning systems. Passive heating disperses heat through natural transfer processes, enhancing interior comfort. Different passive heating solutions can be used, those techniques favor the use of solar energy as it is the essential source of heat. Glazing is the transparent part of the facade, it contributes a significant portion of direct solar gains, and the walls' vast surface area creates a path for thermal transmission, allowing solar radiation to travel through the building in high sunlight. For passive cooling the main bioclimatic design strategies have been focused on reducing solar gains and external heat loads. Resulting in reduced cooling needs, the major techniques for many cities with hot climates are natural ventilation and solar shading for windows (Enteria et al., 2019). Various passive techniques have been described, and each of the above-mentioned strategies can minimize energy use to some amount. A combination of multiple passive approaches is required to obtain a high level of energy performance (Gupta & Tiwari, 2016).

3. Building energy performance indicators

Building energy performance assessment is critical for determining the efficiency of energy use and serves as the foundation for any choice and decision to improve energy efficiency. It can provide building owners and/or occupants with relevant information about how much energy is used and how the performance is compared to benchmarks (Wang et al., 2012). Today, the key indicators used to evaluate building performance are related to energy consumption, but this is a simplified and incomplete evaluation system that does not exploit the full potential of the building structure and cannot guide the user to the optimal improvement. Few authors highlighted the need for new and complete evaluation methods for buildings, and proposed a set of indicators that could be used to better optimize the performance of the existing buildings. The present study is based on indicators proposed by (Chesné et al., 2012), where the authors developed a new set of indicators to assess the building bioclimatic performances. They proposed three type of indicators: the building needs indicators, environmental potential indicators, and building performance indicators. those indicators are introduced in this paper.

First It is possible to negate the impact of an environmental resource (noted as *R*, for example solar radiation) on the building by using dynamic energy simulation. As a result, the needs of the building in the scenario where the influence of environmental resource is removed have been defined as the real needs of the building noted as $b_{Ui-Rj}(t)$, when *U* is the use of the resource (for heating or cooling). The residual need is defined in the typical real-life scenario, where the building could employ those resources $b_{Ui}(t)$.

The second set is the Indicators of potential. As the environmental potential is an important element for the energy of the building, this amount of energy needs to be quantified. The total flux exchanged between the resource Rj and the total envelope of the building at all times is defined at each instant as the total potential $ptot_{Rj}(t)$, given by (eq. 1). Thus, the coincident potential $pconc_{Ui;Rj}(t)$ (eq. 2) is equal to the total potential if there are some building energy needs $b_{Ui-Rj}(t)$, or set to zero. The purpose of this indicator is to know if the resource is globally sufficient to cover the energy needs for a given period, the integrated energy needs have to be compared to the integrated coincident potential. Secondly, another indicator is defined. It is called the adjusted potential $paj_{Ui;Rj}$ (t) and is given by equations 4. It is the portion of the coincident potential that perfectly matches the energy needs.

At each time step, it is calculated as the difference between the energy needs and the coincident potential.

Total potential is equal to:

$$Ptot_{Rj}(t) = \int_{Periode} ptot_{Rj}(t)\, dt \qquad \text{(eq. 1)}$$

Coincident potential:

$$pconc_{Ui;Rj}\,(t) = \begin{cases} ptot_{Rj}(t) & if \quad b_{Ui-Rj}(t) > 0 \\ 0 & \text{Else} \end{cases} \qquad \text{(eq. 2)}$$

The integral of coincident potential over a given period gives the total coincident potential at this period.

$$Pconc_{Ui;Rj}\,(t) = \int_{Periode} pconc_{Ui;Rj}\,(t)\, dt \qquad \text{(eq. 3)}$$

Adjusted potential:

$$paj_{Ui;Rj}\,(t) = \min\left(ptot_{Rj}(t), b_{Ui-Rj}(t)\right) \qquad \text{(eq. 4)}$$

$$Paj_{Ui;Rj}\,(t) = \int_{Periode} paj_{Ui;Rj}\,(t)\, dt \qquad \text{(eq. 5)}$$

Indicators of performance are the third set of indicators. After the quantification of the environmental resources, the next step is to evaluate the exploited part of those resources by the building. To do so it is possible to compare the needs of the building in an environment without and with a given resource. The exploited potential $pexp_{Ui;Rj}(t)$ is calculated as the difference between the energy needs in the simulation without and with the resource at each time step using equations 6 and 7. It is defined as the part of the resource which is actually used by the building. The Indicators that are able to resume the performance of the building are: the cover rate, the exploitation rate, and the generation rate. The cover rate $\tau\ couv_{Ui;Rj}$ (eq. 8) expresses the part of the building's real energy needs which are covered by the resource. The exploitation rate $\tau exp_{Ui;Rj}$ (eq. 9) represents the part of the resource energy that is actually used by the building, and the generation rate is part of the resource energy that create needs for the building (cooling or heating needs) when there is an excess of this energy.

The exploited potential:

$$pexp_{Ui;Rj}(t) = b_{Ui-Rj}(t) - b_{Ui}(t) \qquad \text{(eq. 6)}$$

The integral of exploited potential over a given period gives the total exploited potential at this period:

$$Pexp_{Ui;Rj}(t) = \int_{Periode} pexp_{Ui;Rj}(t) \qquad \text{(eq. 7)}$$

The cover rate:

$$\tau\ couv_{Ui;Rj} = \frac{Pexp_{Ui;Rj}(t)}{b_{Ui-Rj}(t)} \qquad \text{(eq. 8)}$$

The exploitation rate:

$$\tau exp_{Ui;Rj} = \frac{Pexp_{Ui;Rj}(t)}{Pconc_{Ui;Rj}(t)} \quad \text{(eq. 9)}$$

4. Methodology

The set of indicators presented above is used to evaluate the performance of INCAS Building: a single-family experimental house, located at INES Chambery, in South-Eastern France. The reason for choosing to work on this building is that all its characteristics is well known. Multiple studies have been done on this building and the modelling results were compared and validated with previous publications (Chesné et al., 2012. Chahwane, 2012). Therefore, the energy modelling can be considered as reliable.

The glazing area ratio per oriented surface is 36% for the South, 15% for the West, 6% for the East and 4% for the North. There is a south-oriented extended overhang above both ground and upper floor windows to prevent direct solar radiation from entering the building in summer. All windows of the insulated building are double glazed with a total U-value (window and frame) of 1.3 W/ (m2 K) and a solar factor of 0.76. The windows of the old building are single-glazed and their total U-value is 5 W/ (m2 K). The solar factor of the windows is 0.86.

Tab. 1: Non-insulated building envelope configuration.

Wall type	Material	Thickness [cm]	Conductivity [W/m.K]	Density [kg/m3]	Specific heat [J/kg·K]
Exterior wall	Plaster Concrete blocks	2 15	1.15 0.74	1700 800	1000 648
Ground floor	deck slabs	16	1,23	1300	648
Roof	Light wood	16	0,15	500	1200
Internal floor	solid concrete	22	1,75	2400	880

Tab. 2: Insulated building envelope configuration.

Wall type	Material	Thickness [cm]	Conductivity [W/m.K]	Density [kg/m3]	Specific heat [J/kg·K]
Exterior wall	Glass wool Concrete blocks	20 15	0.035 0.74	12 800	840 648
Ground floor	Extruded polystyrene deck slabs heavy concrete	25 16 4	0.029 1.23 1.75	15 1300 2400	880 648 880
Roof	External Rendering MW Stone Wool Timber Flooring	2.5 24.5 0.5	0.5 0.04 0.14	1300 30 650	1000 840 1200
Internal floor	solid concrete	22	1,75	2400	880

The heating set-point is 19 C and the cooling set-point is 26 C. In both configurations, night ventilation is planned during summer (from the beginning of June to the end of August) with a ventilation rate of 4 vol/h between 10 pm and 7 am. Otherwise, the ventilation rate is 0.5 vol/h. An occupancy scenario is integrated to the simulation. The air infiltrations are considered equal to 0.04 vol/h. The scenario of total power dissipated by both inhabitants and household appliances is given in table 03

A non-insulated and two insulated versions of the building (insulated from the inside and outside) will be studied and compared. The purpose of this study is to evaluate a set of building performance indicators by applying them to various building configurations, then to evaluate the performance of three different building configurations and select the building that performs best in terms of energy consumption and resource exploitation. Although the indicators used in this study are still in the theoretical stage, using them could provide insight into their limitations and pave the way for future advancements.

The building is modelled in Design Builder, then the simulation is run using EnergyPlus. The adopted model consists of two zones. Each zone is on one per level, and three configurations of the INCAS building are studied.

The first one is a non-insulated building (before retrofitting), then the next two buildings' configurations are different only in insulation type: interior or exterior. The Thermal bridges have not been taken into consideration, the wall compositions for the two versions of the INCAS house are listed in table 1 and table 2.

Tab. 3: Daily scenario of the total power dissipated

Hours	0-6	7	8	9-16	17	18-19	20	21	22	23	24
Power [W]	340	830	730	20	570	730	950	1030	830	810	340

5. Results and Discussion

The simulation's results "from the 19th to the 29th of January in the 3 types of buildings" are expressed as graphs that show the application of earlier indicators in the case study of the INAS building. The three types of indicators will be presented in different graphs to assess the solar potential and building performance, and to draw conclusions about the presented indicators.

5.1 Building energy needs:

The results of the building simulation for the first set of indicators, which describe the building's heating demands, are shown in figure 1, figure 2 and figure 3. The three types of building configurations (Non-insulated building, interior insulation, and exterior insulation) are presented in the same figure. The results show in the three types of buildings, the real heating needs are greater. It is the case where the solar potential is null. That means that the sun covers a part of the building's heating needs, so it reduces the building's energy consumption. By analysing the building heating needs graph, it can be noticed that this value decreases each day to very low values, then go higher, the lowest value is located almost in the middle of each day when the solar potential is in its highest value. Those results highlight that the sun is a source of heating that compensate for the heating energy of the building.

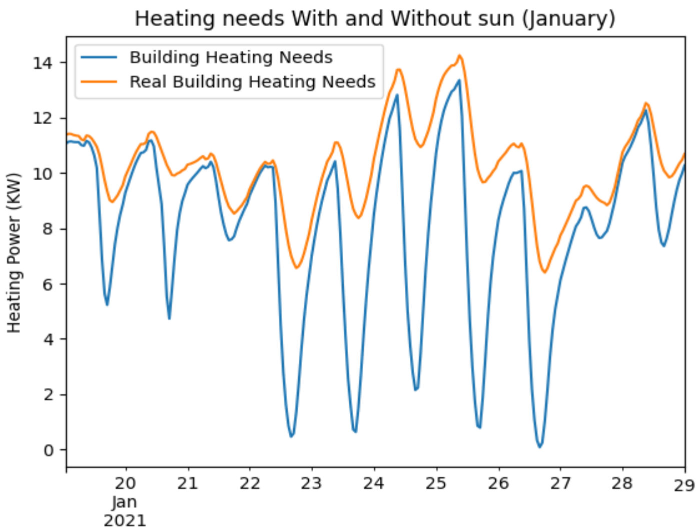

Fig. 1: Need indicators result in Non-Insulated building

When comparing the three configurations, the non-insulated building shows the highest consumption at a maximum of 14kW. The exterior and interior insulation graphs have almost the same shape, while the lowest building consumption is in the exterior insulation building. As the wall's materials compositions are the same in both interior and exterior insulated buildings, both transfer heat in the same way. The thermal bridging is neglected in this simulation, so the only parameter that made a difference is the placement of the insulation. That leads us to a conclusion that the exterior insulation is a better design, this could be due to better use of thermal mass or this configuration improves the building performance on the exploitation of solar energy. More investigation is needed to validate those assumptions using the other type of indicators.

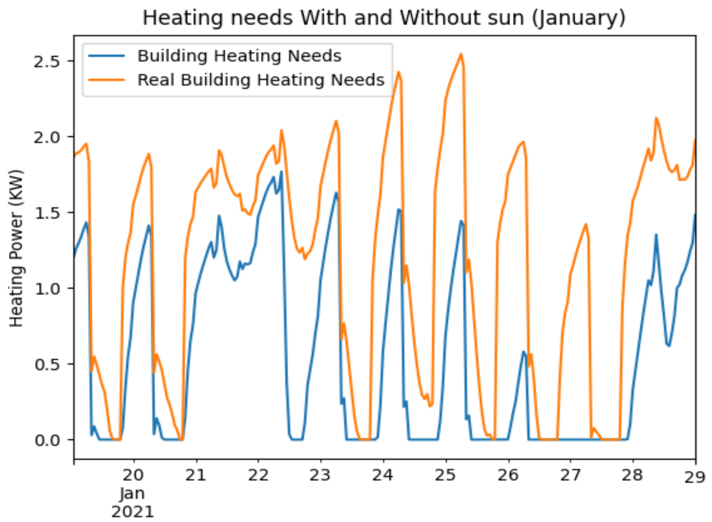

Fig. 2: Need indicators result Interior insulated building

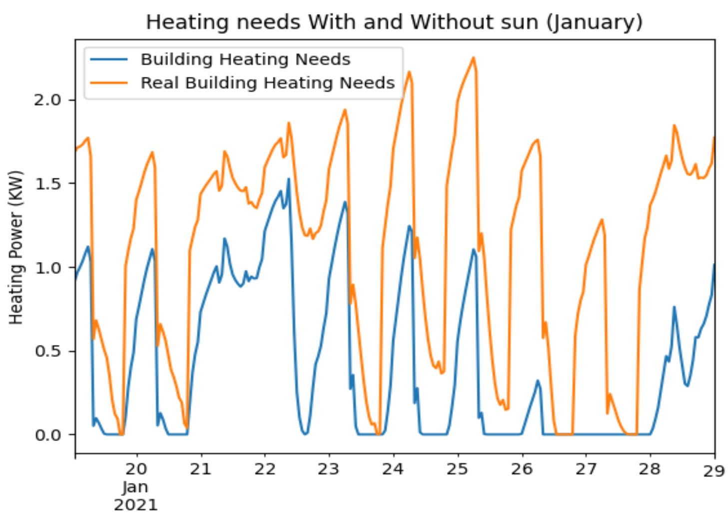

Fig. 3: Need indicators result Exterior insulated building

Need indicators show the capacity of identifying the type of energy source (heat source or heat sink), and compare the performance of the building design. The heating needs is the type of energy consumption indicators that is most used in research, and by removing the influence of one energy source (Sun in this case of study) it will make it a superior indicator that can provide more information about the building and its surrounding. but it is still limited because it doesn't qualify the environment energy potential, and justify the reason for the better performance of a building, and how it can be improved.

5.2 Environmental energy potential:

To assess the available energy in the building surrounding, the potential indicators have been introduced. Figure 3, Figure 4 and Figure 5 present the building's simulation results using potential indicators. The building total solar incident radiation, is the amount of solar energy incident on the total surface of the building envelope. When building needs energy for heating, the coincident potential (concomitant potential) is equal to the total incident solar energy. In the case of a non-insulated building, the graph of both indicators is superposed, which means that there is always heating needs for the building. When in insulated buildings the concomitant potential goes to zero at some hours on days 27 and day 28, which means that no heating energy is required for the building at those hours of the day. In the three buildings the concomitant potential is higher than the building needs during the day hours, which means that at those hours, theoretically, the building heating needs can be covered completely by the solar energy incident on the envelope of the building.

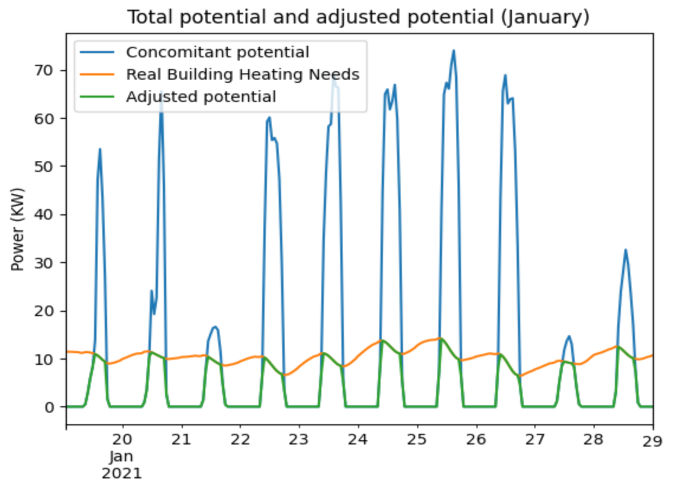

Fig. 4: Potential indicators results for Non-insulated building

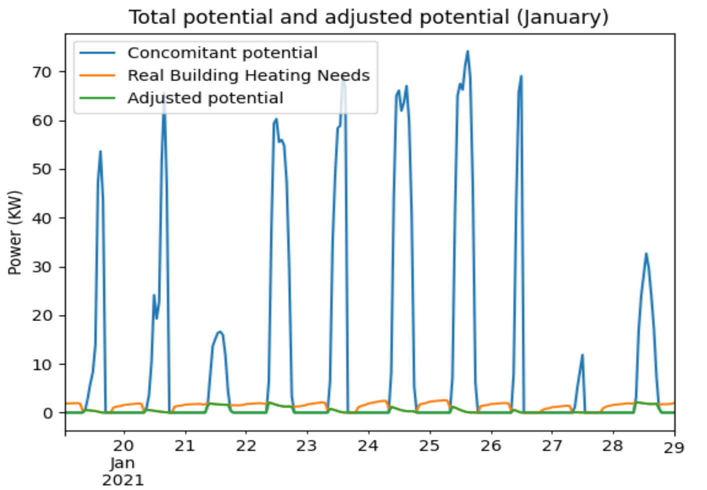

Fig. 5: Potential indicators results for interior insulated building

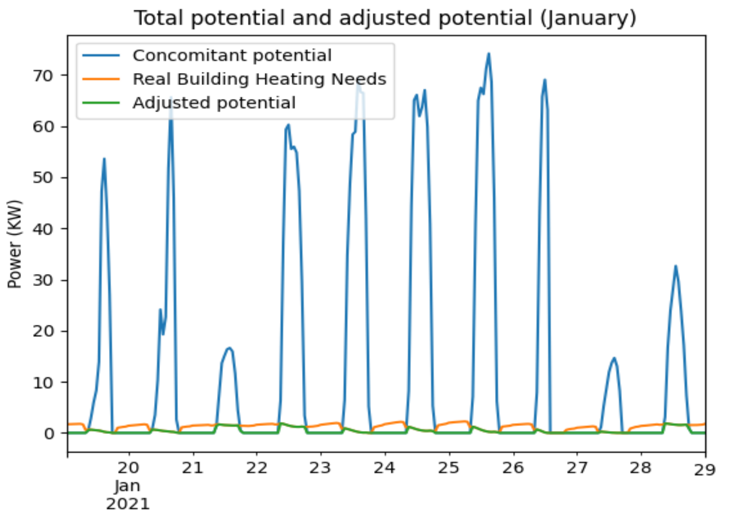

Fig. 6: Potential indicators result for exterior insulated building

The adjusted potential presented by the green graph, is the amount of energy required to use from the concomitant. potential, it goes to zero when there is no solar potential (at night) and is always lower than the building needs, in another word it is the useful part of the resource, that is to say the part that meets the building needs. When comparing the three cases, the concomitant's potentials and adjusted potential are higher in non-insulated building, because there are more heating needs and slightly lower in the building insulated from the inside. After all, there are more hours when the heating needs are null.

The concomitant potential indicator is not an indicator capable of evaluating and comparing the performance of buildings, the purpose of this indicator is to evaluate the environmental energy potential and its capacity to cover the building needs. The indicators also show the intersection between the demand and the energy potential, those kinds of information could be useful for studying thermal storage in the building.

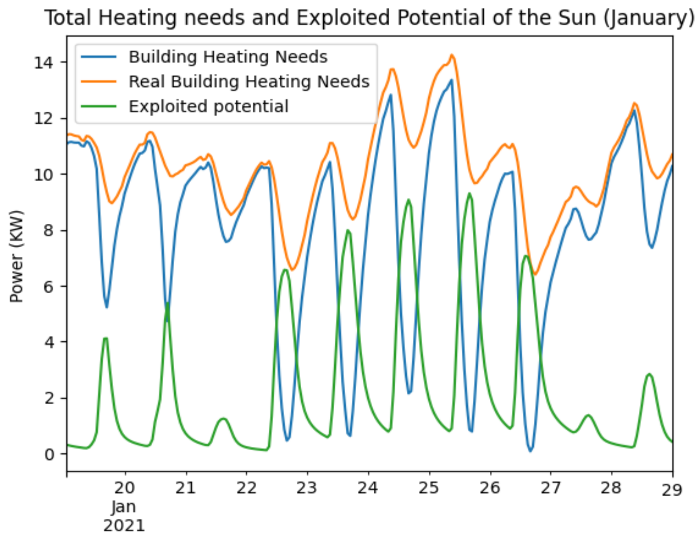

Fig. 7: Sun exploited potential result for non-insulated building

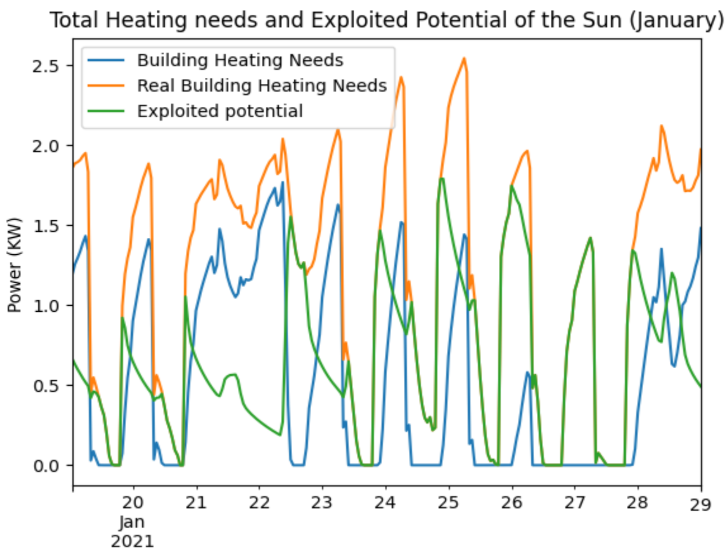

Fig. 8: Sun exploited potential result for interior insulated building

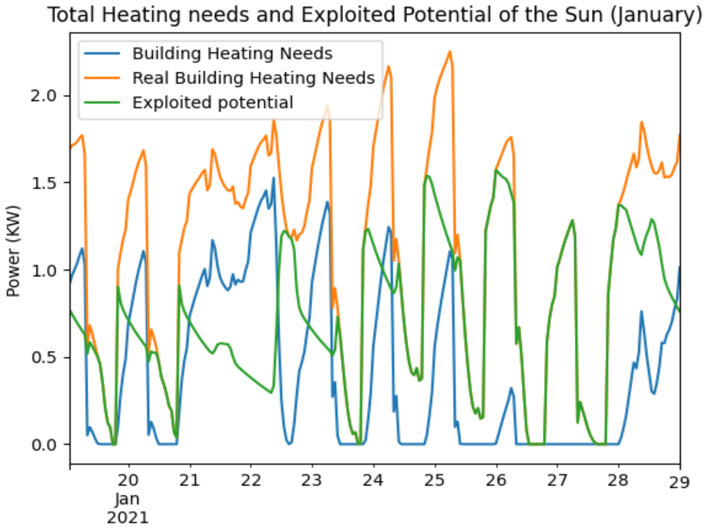

Fig. 9: Sun exploited potential result for exterior insulated building

Another important parameter is presented as exploited potential (figure 03). It is the difference between the residual and the real heating needs of the building, it represents the part of solar energy that is exploited by the building and provides for some of the heating needs. The sun potential is maximal at mid-day, that's why the building heating needs are the lowest and the exploited potential is the highest at that time. At night there is no sun, and by looking at the case of a non-insulated building, the value of exploited potential is almost never zero. that means that the building uses the sun's energy for heating even at night time, the explanation of that is that the energy is stored in building walls by thermal massing, and released gradually at night.

In the case of insulated buildings, the heating needs are considerably lower, the sun could cover the total heating needs of the building, which have been shown in the superposed graphs of real heating needs and exploited potential. The comparison between the performance of both interior and exterior insulation buildings is not so clear in this type of indicator and representation, the exterior insulation building shows a slightly better exploitation performance. The next parts of this study will include the integrated results for the whole period to validate for more conclusions.

The previous potential indicators are a useful tool to evaluate the building capacity of using the environmental energy, it defines the relationship between the building and its environment. This indicator can be used to evaluate the capacity of a building to store energy by thermal mass or to design a thermal storage system that uses that energy during the high consumption hours generally at night in residential buildings, to provide better comfort and less energy consumption.

5.3 Building performance evaluation:

The prior analysis utilizing need and potential indicators were useful in assessing the energy demands of the building and its environment, but it was not sufficient to fully compare the performance of each case study, which is why performance indicators were included. These percentage-based indicators are comparable numbers that summaries each building's performance and identify the most effective design. Figure 4 presents the exploitation and coverage rate for the three types of buildings, when comparing the three cases the coverage rate improved from 2.9% in the non-insulated building to 63% in the exterior insulated building. This is because the energy needs are lower on insulated building cases. The exploitation rate shows a decrease from 17% in Non-insulated buildings to 5% in the case of external insulation. That proves that the thermal insulation separates the building from the exterior environment, and decrease its capacity of exploiting the energy from its surrounding. The building performance and its energy consumption could be improved by applying the proper technics to increase its exploitation rate, on the same side as improving its insulation. The most suitable solution is to find a compromise between those values by applying the fitted passive technics to optimize the energy performance of the building.

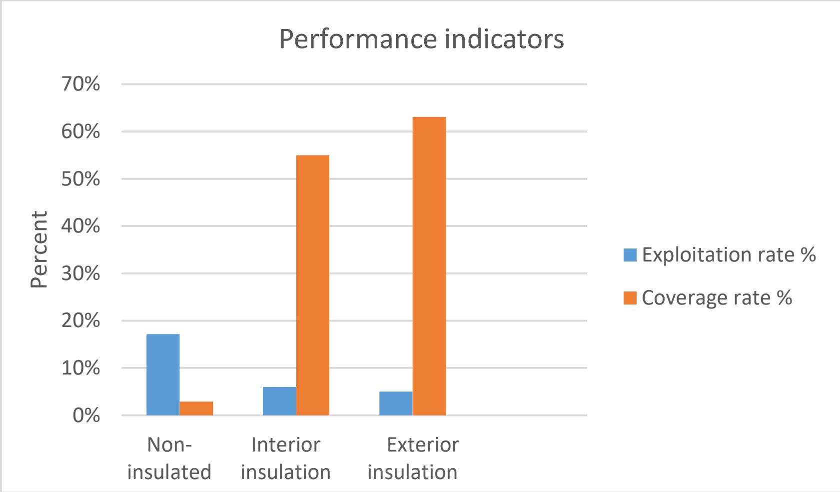

Fig. 10: Performance indicators result of the 3 different configurations of INCAS building.

Table 4 presents a summary of the previously studied indicators, the values in the table are an integral values for the 10-day of study. Those values will be used to come to conclusions regarding the performance of each case study. Passing from a non-insulated building to an insulated building significantly reduces the heating needs, and this is reducing the concomitant potential. The lowest building consumption is in the exterior insulation case, the exploitation rate shows the opposite result because the non-insulated buildings use more solar energy to provide for their heating needs. The comparison of the three buildings makes the exterior insulated building better in performance. It has the lowest heating needs and the highest coverage rate, in the opposite, the exploitation rate is so low, around just 5,8%. According to table 4, the external insulated building's exploited potential value is greater, but the concomitant potential is higher. The value of the exploitation rate is lower because it is the value of exploited potential divided by the concomitant potential that results make it lower.

Tab. 4: Energy performance indicators, result of the 3 different configurations of INCAS building.

	Non-insulated building	Interior insulation	Exterior insulation
Building Heating Needs [kWh]	1923	129	99
Real Building Heating Needs [kWh]	2462	287	268
Concomitant potential [kWh]	3143	2666	2922
Adjusted potential [kWh]	845	67	68
Exploited potential [kWh]	539	158	169
Exploitation rate %	17,13	5,93	5
Coverage rate %	2,9	55	63,1

By using the previous indicators, we were able to examine the building's performance and determine the most effective configuration. However, this study is incomplete, in terms of envelope evaluation. The indicators were only used to evaluate the building as a whole when those indicators could be adopted to evaluate each part of the building envelope (walls, ceiling and windows). The extensive analysis of the envelope might give more information about the building's principal thermal loss locations and the thermal behavior of each component. Those sets of data could be used to better optimize the envelope performance adapting retrofitting at each part of the building envelope.

This study only considers solar potential as a source of energy for the building, during the period of winter, when all the other natural energy resources should be considered and well evaluated (Air, sky...etc.). Those energy natural potentials could be seen as a source of energy that reduces the building energy consumption, for a period of time. In another period, the same potential could create more needs and increase energy consumption, for example, when studying solar potential, it is the main heating source, it provides heating in winter while in summer it creates cooling needs. So, depending on the season and weather, all-natural energy potentials should be evaluated in terms of how much energy it provides and how much needs it creates.

The generation rate was introduced in this study as this part of the resource energy potential that creates a need for the building, it was not evaluated in this study because the resources potential that generates needs in winter was not evaluated. The importance of evaluating all the potential resources and their contribution to the energy balance of the building is to improve the building capacity to exploit the sources that provide energy and to protect against or eliminate the sources that create more needs for the building, depending on local climates and seasons.

There are various limitations to the indicators employed in this study, the basic idea for those indicators is that the simplest way to value a resource, is to do it instantaneously. The indicators consider only the energy portion of the resource available when there is a need for it, otherwise, when there is no need, the resources are assumed to be zero. Realistically, this is not the case, because the energy resources could never disappear, and the thermal phase shifting of the building must be considered.

Adopting the evaluation process only on the simultaneity of energy resources and building needs, excludes the possibility of optimizing the coverage of resources by thermal storage. At the time steps when there are no building energy needs, the environmental energy potential should be evaluated as an excess of energy that could be stored for later use, as it can create another need for the building and need to be evacuated. Giving example by solar energy in mid-season, the thermal energy could create a need for cooling in the building as it can be stored to be used for night heating.

Another improvement is suggested for the definition of exploitation rate, this indicator is in direct relationship with concomitant potential, as seen in the analysis results, the concomitant potential changes when changing the building envelope, which influences the exploitation rate and makes it a non-comparable parameter. The suggested improvement is to make this indicator depends on the total potential rather than the concomitant potential. Finally, the presented indicators were based on energy simulations of buildings with and without the presence of environmental resources. In our case, the cancellation of the effect of certain environmental energy resources could lead to a dynamic of unrealistic thermal behavior of the building. The investigation of more realistic methods on the same side using the present evaluation method is recommended for the upcoming studies.

6. Conclusion

In this study, we used a comprehensive set of indicators to evaluate and compare the performance of three different single-family house building configurations. Unlike traditional evaluation methods, which focus mainly on the building envelope as a source of energy losses, our approach takes into account the building's ability to harness and exploit energy from its surroundings.

The findings show that exteriorly insulated buildings have the lowest energy requirements when compared to non-insulated and interiorly insulated buildings. It is important to note, however, that this configuration has a low exploitation rate of only 5%. This limitation comes from its ability to restrict heat exchange between the building and the external environment, preventing solar heat absorption by the building envelope from reaching the interior spaces.

While insulation is an effective solution for reducing heating losses in buildings, it also creates a barrier between the building and its surroundings, reducing the structure's bioclimatic performance. Additional investigation is needed to strike a balance between increasing insulation levels and improving the building's ability to exploit solar resources. While insulation is an effective solution for reducing heating losses in buildings, it also creates a barrier between the building and its surroundings, reducing the structure's bioclimatic performance. More research is needed to strike a balance between increasing insulation levels and improving the building's ability to exploit solar resources. Windows play a crucial role in solar radiation transmission, while walls primarily influence heat exchange with the exterior environment. Analysing the performance of each part of the envelope walls individually, taking into account different orientations, will yield valuable insights. To gain a clearer understanding of the overall behaviour of the building it is also important to separately consider the specific effects on windows and walls, a more detailed analysis is needed to differentiate the impact of solar radiation on windows versus walls.

The aforementioned indicators provide a solid foundation for evaluating building performance, comparing various configurations, and determining the most effective approach. These measures will serve as the foundation for the creation of a new, effective evaluation technique aimed at optimizing building performance and reducing energy consumption. The next steps in this research will be to analyse additional scenarios and building configurations to maximize building performance, as well as to investigate innovative indicators and passive construction techniques. We can improve our understanding and contribute to advancements in sustainable building design and construction practices by doing so.

7. Acknowledgments

This work has been supported by the French National Research Agency, through Investments for Future Program (ref. ANR-18-EURE-0016 – Solar Academy). The research units LOCIE and LISTIC are members of the INES Solar Academy Research Hub.

8. References

Bajcinovci, B., & Jerliu, F. (2016). Achieving Energy Efficiency in Accordance with Bioclimatic Architecture Principles. 18(December), 54–63. https://doi.org/10.1515/rtuect-2016-0013

Budescu, M. (2013). Bioclimatic architecture , a sensible and logical approach towards the future of building development. Lxiii.

Chahwane, L. (2012). Valorisation de l ' inertie thermique pour la performance énergétique des bâtiments To cite this version : HAL Id : tel-00701170 Valorisation de l ' inertie thermique pour la performance énergétique des bâtiments.

Chesné, L., Duforestel, T., Roux, J.-J., & Rusaouën, G. (2012). Energy saving and environmental resources potentials: Toward new methods of building design. Building and Environment, 58, 199–207. https://doi.org/10.1016/j.buildenv.2012.07.013

Enteria, N., Awbi, H., & Santamouris, M. (2019). Building in hot and humid regions: Historical perspective and technological advances. Building in Hot and Humid Regions: Historical Perspective and Technological Advances, 1–219. https://doi.org/10.1007/978-981-13-7519-4

Gupta, N., & Tiwari, G. N. (2016). Review of passive heating/cooling systems of buildings. Energy Science and Engineering, 4(5), 305–333. https://doi.org/10.1002/ese3.129

Manzano-Agugliaro, F., Montoya, F. G., Sabio-Ortega, A., & García-Cruz, A. (2015). Review of bioclimatic architecture strategies for achieving thermal comfort. Renewable and Sustainable Energy Reviews, 49, 736–755. https://doi.org/10.1016/j.rser.2015.04.095

Ness, M. (2017). review and analysis in cold climates – principles and tools for bioclimatic building design - an applied review and analysis in cold climates –. July.

Sadineni, S. B., Madala, S., & Boehm, R. F. (2011). Passive building energy savings: A review of building envelope components. Renewable and Sustainable Energy Reviews, 15(8), 3617–3631. https://doi.org/10.1016/j.rser.2011.07.014

Wang, S., Yan, C., & Xiao, F. (2012). Quantitative energy performance assessment methods for existing buildings. Energy & Buildings, 55, 873–888. https://doi.org/10.1016/j.enbuild.2012.08.037