EXPLOITATION OF THE ENVIRONMENTAL ENERGY RESOURCES: INDICATORS AND DESIGN STRATEGIES

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ABSTRACT

Assuming that isolating a building might not be the best solution to exploit the free renewable sources of its environment (outside air temperature, sky temperature, solar radiation…), a first identification step has been carried out to determine which sources should be exploited. Building energy simulations have been carried out, including various isolation levels and climatic conditions. Then, indicators have been defined in order to quantify the ability of the previous sources to cover the energy needs and the possibility for the building to exploit them. When the source's capacity is not sufficient, a new energy management system has also been tested. Then, the previous indicators have been transposed at the scale of each wall. It has been necessary to do so in order to differentiate the high-capacity surfaces where new systems could be designed and implemented, from the low-capacity surfaces that should simply be insulated.

INTRODUCTION

Since the 1970s, when the energy savings issues have emerged, the construction and retrofitting of buildings have mainly been focused on insulation Indeed it was the easiest and cheapest way for reducing the consumption of expensive or polluting energies. However, insulating a building from its environment deprives it from the renewable free energy sources, either they are heating or cooling sources. The aim, after having selected the sources, is to quantify their influence on energy needs in order to assess their capacity to cover the building's immediate energy needs and the ability of the building to exploit them.

RESOURCES' IDENTIFICATION

One heating source: the sun

The first and the most important environmental resource for heating is the sun. The solar spectrum ranges from the infrared (53%) to the ultraviolet (7%) including the visible radiation (40%) ([Munroe et al., 1981] and [Gueymard, 2004]). The incoming solar radiation on a wall has two origins (Figure 1). The direct radiation which depends on the wall's exposure and the sun's position. The diffuse radiation coming from the radiation absorbed and emitted by the atmosphere and the radiation reflected by the environment which depends of the albedo and the tilt angle of the wall. The solar radiation is obviously characterised by its day-night periodicity.

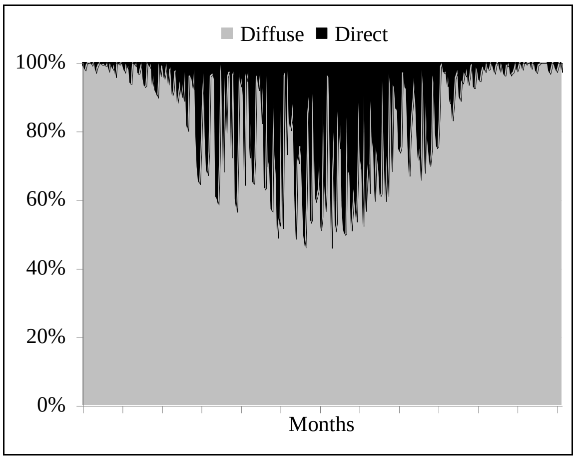

Figure 1 : Year-round horizontal global solar radiation in Chambéry

Two cooling sinks: the sky and the air

The exterior walls of a building loose energy by long wave radiation toward their environment, one part of which being the sky. The radiative exchange with the sky can be modelled thanks to the sky vault model to which a sky temperature is allocated. Most of the time this temperature is the temperature of the corresponding black body so that the radiation exchanges' models are simpler. This temperature can be obtained from the ambient air, the relative humidity, or the cloud cover. Several models exist and integrate these parameters to different levels ([Adelard et al., 1998], [Pandey et al., 1994], [Martin et al., 1984] and [Kasten et al., 1980]). In all cases we notice that the sky temperature is lower than the ambient air, and this difference is higher in summer that makes the sky a very interesting energy sink for summer comfort (Figure 2).

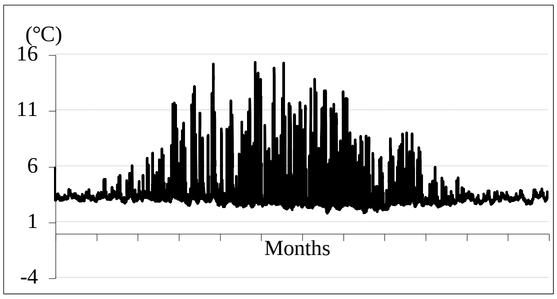

Figure 2: Year-round difference between the air and the sky temperature in Chambéry

The outside air which is characterized by its temperature is often used as a cooling mean thanks to summer night ventilation. Indeed it is the period when the day and night temperature's differences are the most important (Figure 3).

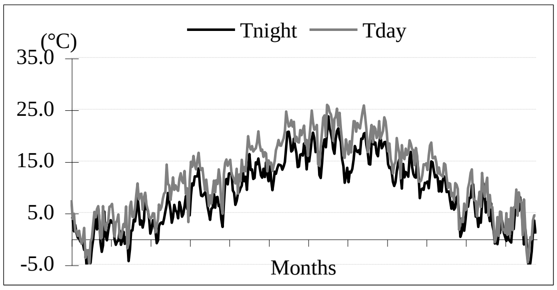

Figure 3: Year-round outside air's daily and nocturnal temperatures in Chambéry

SIMULATION

The results presented in this paper have been obtained from simulations of a single house carried out with EDF's modeling software CLIM2000 [Rongère et al., 1993]. The house is the two-storey INCAS house (Figure 4) located at the French Solar Energy Institute (INES) in Chambéry [Brun et al., 2009].

Figure 4: The INCAS house in Chambéry

The building has been modeled with two versions: a non-insulated version, as houses were built before 1974 and which now need to be retrofitted and a high performance version according to the criteria of the low-energy building. Both versions have been simulated under two French climates: Chambery's climate, representing a cold climate (cold winter and fresh summer) and Marseille's climate, representing a moderate climate (mild winter and hot summer). The model is a two-zones model with a crawl-space and a ventilated attic. The roof's capacity has not been taken into account in this since it is supposed to be already used for hot water and PV production. In each zone, a heating/cooling system is supposed to control air temperature.

Since the main purpose is to quantify the impact of the sources on the building's energy needs, two cases were simulated: with and without each source. Depending on the source, this suppression was made differently:

- the incoming solar radiation was set to zero,
- the sky temperature was supposed equal to the outside air temperature so that long-wave radiations occur only between the building and the environment ,
- the ventilation was stopped (instantaneous influence of outside air temperature).

Most of the indicators that we are going to define in this paper rely on the simultaneity between the resource availability and the energy needs covered by the very resource. In the rest of the paper, we consider Q and Q^* respectively the energy needs with and without the resource. Except for ratios, all the indicators are calculated at each time step, then integrated over the simulaition period. To make the reading easier, the result are then divide either by the living area or by the wall's surface whether the indicator is calculated at the scale of the building or the wall. In each case the simulation period is the whole year, so the indicators presented here have the same unit : kWh/(m².year).

RESOURCES' QUANTIFICATION AT THE SCALE OF THE BUILDING

Once the main energy resources are known, it is now necessary to see if these resources meet the energy needs of the building. There is a dual purpose : on one hand to assess the capacity of the resource to cover the building's need and on the other hand to estimate the ability of the building to exploit the resources.

Indicators of capacity

The first indicator gives the whole energy that the resource is able to exchange with the building whatever its energy needs. Its definition depends of the resource.

The total capacity of the sun is the total solar radiation that hits all the building's walls .

$$\Pi_{TOT,sun} = \sum_{walls} \left(\phi_{direct} + \phi_{diffuse}\right) S_{wall}$$

The total capacity of the sky is the net total radiation exchanged between the sky and the building's wall considered at ambient outside air temperature. This definition allows us to take into account only the radiation with the sky and not with the rest of the environment.

$$\Pi_{TOT,sky} = \left| \sum_{walls} F\varepsilon\sigma \left(T_{out}^{\ 4} - T_{sky}^{\ 4} \right) S_{wall} \right|$$

The total capacity of the air is the total enthalpy exchanged between the outside and the inside air at set temperature with a fixed ventilation rate (equal to 10 vol/h in this study).

$$\Pi_{TOT,air} = \left| \dot{m} C_p (T_{regulation} - T_{out}) \right|$$

with $\dot{m} = \dfrac{\rho_{air} V_{in} \tau_{ventil}}{3600}$

To limit energy storage, it is crucial to know the availability of the resources when the building needs them. The coincident capacity of a resource is defined as its total capacity which coincides with the building's need that the resource is likely to cover. At each time step, it is either equal to the total capacity or to zero.

$$\Pi_{COINC} = \begin{vmatrix} \Pi_{TOT} & if > 0 \\ 0 & if \left| Q^*_{cov} \right| = 0 \end{vmatrix}$$

The adjusted capacity is the minimum between the total capacity and the corresponding energy needs.

$$\Pi_{ADJ} = \min(\left|\Pi_{TOT}\right|, \left|Q^*_{cov}\right|)$$

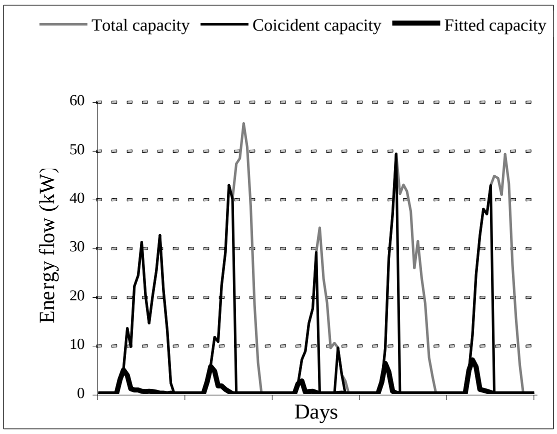

Figure 5: Diagram principle of the capacity indicators

Table 1 shows that in almost all cases the amount of available energy in the environment to heat and cool the building in each situation is greater than the real matching energy needs. The difference is from 5 to 25 for the high-insulated building and only 2 to 3 for the low-insulated one. Thus, the energy needs of the low-insulated building may be more difficult to be covered by each source. The only exception is the case of the high-insulated building in Marseille for which the cooling capacity of the air is lower than the building's cooling loads.

Table 1: Capacity indicators for the single house over a year

Source	**Climate**	**Insulation level**	**Coincident capacity**	**Real energy needs**	**Adjusted capacity**
Sun	Marseille	High	659.2	25.6	13.4
		Low	833.0	295.0	115.3
	Chambéry	High	743.1	59.0	27.5
		Low	957.6	478.5	180.9
Sky	Marseille	High	213.7	36.9	36.9
		Low	82.4	43.9	41.7
	Chambéry	High	48.6	8.8	8.7
		Low	17.9	9.6	7.9
Air	Marseille	High	520.9	64.6	49.0
		Low	**33.6**	**39.0**	**10.9**
	Chambéry	High	471.3	44.2	39.1
		Low	18.6	10.6	4.8

Indicators of performance

After the available energy that the building needs has been determined, it is necessary to know how the building exploits it so that we can compare and evaluate the different cases.

The exploited capacity of the resource is the difference between the energy needs, with and without the resource, likely to be covered by the source in question.

$$\Pi_{EXP} = \left|Q^*_{cov}\right| - \left|Q_{cov}\right|$$

The exploitation rate is the ratio between the exploited and the coincident capacity. It comes from the solar efficiency's formula defined by Pierre Tittelein in his PhD thesis [Tittelein, 2008].

$$Exp_{rate} = \frac{\Pi_{EXP}}{\Pi_{COINC}}$$

The coverage rate is the ratio between the exploited capacity and the corresponding energy needs without the source.

$$Cov_{rate} = \frac{\Pi_{EXP}}{\left|Q^*_{cov}\right|}$$

Table 2: Performance indicators for the single house over a year

Source	Climate	Insulation level	Exploited capacity	Coverage rate	Exploitation rate
Sun	Marseille	High	25.4	99%	4%
		Low	102.3	35%	12%
	Chambéry	High	44.8	76%	6%
		Low	117.2	24%	12%
Sky	Marseille	High	4.0	11%	2%
		Low	10.3	23%	12%
	Chambéry	High	1.2	13%	2%
		Low	2.6	27%	15%
Air	Marseille	High	31.7	49%	6%
		Low	5.4	14%	16%
	Chambéry	High	36.5	83%	8%
		Low	3.6	34%	19%

Table 2 shows that whatever the situation the energy needs are better covered for the high-insulated building than for the low-insulated one even if the difference is clearly greater for the heating needs than the cooling needs. It is interesting to notice that the sky has a very low coverage rate over the building's cooling needs.

Indicators of generation

The considered resource has also a negative effect : it generates thermal needs opposite to the nature of the resource. The generated need is the difference between the previous needs, with and without the resource.

$$\Pi_{gen} = \left|Q_{gen}\right| - \left|Q_{gen}^{*}\right|$$

The generation rate is the ratio between the generated needs and the corresponding needs with the resource.

$$Gen_{rate} = \frac{\Pi_{gen}}{\left|Q_{gen}\right|}$$

Table 3 shows that whatever the situation all the cooling needs are bred by the sun whereas the heating needs are differently generated according to the climate and the isolation degree. The sky has a very limited consequence over the heating needs of the building except for the high-insulated version in Marseille for which the heating energy needs are insignificant. The air is responsible for a considerable part of the heating needs in Chambéry's climate.

Table 3: Generation indicators for the single house over a year

Source	Climate	Insulating level	Generated needs	Generation rate
Sun	Marseille	High	32.8	100%
		Low	32.9	98%
	Chambéry	High	7.6	100%
		Low	7.0	100%
Sky	Marseille	High	0.1	30%
		Low	25.5	13%
	Chambéry	High	1.3	9%
		Low	19.3	5%
Air	Marseille	High	0.1	65%
		Low	25.1	13%
	Chambéry	High	7.7	54%
		Low	49.4	14%

RESOURCES' MANAGEMENT

According to Table 1 it seems that the cooling needs could be easily covered by the exchanges with the sky and the air since the adjusted capacity of both sinks is very close to the building's needs. Moreover these two sinks can be combined. On the contrary, the adjusted capacity of the sun is twice lower than the building's heating needs even if the coincident capacity is largely higher. It appears that the energy management procedure which has been applied there does not match the nature of this source which is free, intermittent and disproportionate in comparison with the building's heating needs. Thus, it appears interesting to test a management procedure that would be able to take advantage of environmental resources. We discuss this point in the following paragraphs.

Principle

When the resource is limited, non renewable and expensive it is easy to understand that the management mode is designed to maintain a minimum comfort inside the building, by using as few energy as possible to meet a fixed set point. Since the energy coming from the sun is renewable, free, and largely sufficient, it is conceivable to adapt the management system to use as much energy as possible even it that increases the comfort level. An adaptative set point is thus going to be define beyond the fixed set point and will be used when the resource exists. In the simulation, we assume that the building's walls are able to collect all the incoming solar energy and to transmit it instantly and integrally to the inside air. If the coincident capacity is positive, we use this ideal system to increase the comfort as long as the air temperature lies beneath the adaptative set point. If this energy is not sufficient to maintain a minimal comfort, or if the coincident capacity is nil, the internal heating system is then activated. Thus, a single temperature is not used anymore, but a range of temperatures.

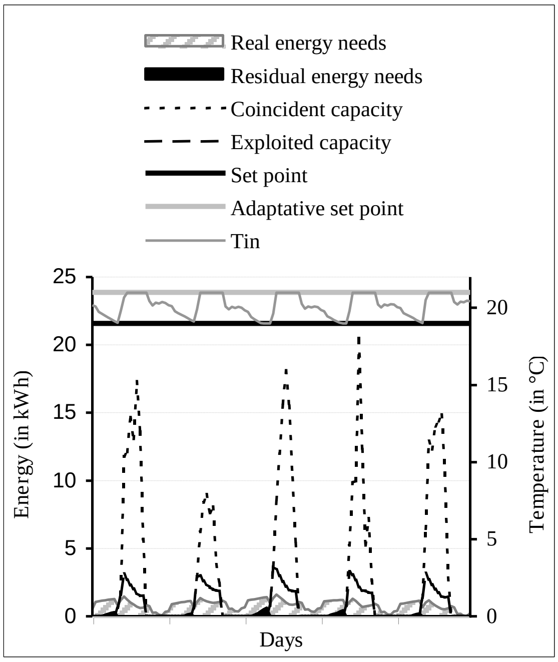

Figure 6: Principle of the adaptative set point

Results

The previous energy management system is obtained by using the simulation without sun to which an ideal power generator is added.

Table 4: Performance indicators for the high-insulated single house over a year

Mode	Climate	Exploited capacity	Residual needs	Coverage rate	Exploitation rate
Fixed set point	Marseille	25.4	0.2	99%	4%
	Chambéry	44.8	14.2	76%	6%
Range 1°C	Marseille	23.9	1.7	93%	4%
	Chambéry	45.6	13.4	77%	6%
Range 2°C	Marseille	25.6	0.0	100%	4%
	Chambéry	54.9	4.1	93%	7%
Range 3°C	Marseille				
	Chambéry	58.4	0.6	99%	8%

Table 4 shows that the low heating needs of the high-insulated building are covered very quickly by the sun with the new management system even if the exploitation rate remains constant and very low.

Table 5: Performance indicators for the low-insulated single house over a year

Mode	Climate	Exploited capacity	Residual needs	Coverage rate	Exploitation rate
Fixed set point	Marseille	102.3	192.7	35%	12%
	Chambéry	117.2	361.3	24%	12%
Range 1°C	Marseille	130.0	165.0	44%	16%
	Chambéry	196.5	282.0	41%	21%
Range 2°C	Marseille	142.2	152.8	48%	17%
	Chambéry	210.5	268.0	44%	22%
Range 3°C	Marseille	153.6	141.4	52%	18%
	Chambéry	223.0	255.5	47%	23%
Range 4°C	Marseille	163.9	131.1	56%	20%
	Chambéry	234.3	244.2	49%	24%
Range 5°C	Marseille	173.3	121.7	59%	51%
	Chambéry	244.7	233.8	51%	26%
Range 6°C	Marseille	182.2	112.8	62%	22%
	Chambéry	254.1	224.4	53%	27%

Table 5 shows that the wider the temperatures' range is, the better the heating needs of the low-insulated building are covered and the better the sun's capacity is exploited. In comparison with the standard simulation with a fixed set point, the coverage and exploitation rate have almost doubled as far as it concerns Marseille's climate, and more than doubled in the case of Chambéry's climate. The sun covers almost 2/3rd of the heating needs in Marseille and more than the half of the heating needs in Chambéry when the temperatures' range is equal to 6°C. However this increase is very slow and does not lower the needs to a reasonable point. Thus, it is necessary to identify the walls that have a very low capacity and exploitation ability to treat them in order to decrease the energy needs.

RESOURCES' QUANTIFICATION AT THE SCALE OF EACH WALL

The previous indicators defined for the whole building can be adapted for each wall. It will be helpful to discriminate between the walls that have a high-energy capacity but a low ability to exploit it and the walls that have a poor energy capacity and may be isolated. At this scale only the two resources which exchange with the building through a flow of energy by its walls remain: the sun and the sky.

Indicators of capacity

The total capacity is the whole flow of energy per surface exchanged between the environment and the wall.

The coincident capacity is the total capacity that coincides with the area's corresponding energy needs.

Indicators of performance

At the scale of each wall, the exploited capacity is the resource's quantity that is actually used by the wall to cover the area's energy needs. Indeed, at each time step, a flow of energy occurs between the wall and the inside air. This flow is proportional to the difference between the wall's temperature and the comfort's temperature for which the needs, likely to be covered by the resource, are calculated. Considering φ_{cov} this flow. Then,

$$\varphi_{\text{cov}} = \begin{vmatrix} h\,(T_w - T_{c,\text{cov}}) + \phi_{trans} & if \quad \left|Q^*_{\text{cov}}\right| > 0 \\ 0 \quad otherwise & \end{vmatrix}$$

Whether φ_{cov} contributes either to decrease or to increase the previous needs, it will respectively be considered φ^-_{cov} or φ^+_{cov}.

$$\begin{cases} \varphi^-_{\text{cov}} = \begin{vmatrix} \varphi_{\text{cov}} \quad if \quad \varphi_{\text{cov}}.Q^*_{\text{cov}} > 0 \\ 0 \quad otherwise \end{vmatrix} \\ \varphi^+_{\text{cov}} = \begin{vmatrix} \varphi_{\text{cov}} \quad if \quad \varphi_{\text{cov}}.Q^*_{\text{cov}} < 0 \\ 0 \quad otherwise \end{vmatrix} \end{cases}$$

The resource has a dual-effect upon φ_{cov}. It increases φ^-_{cov} and decreases φ^+_{cov}. The flows' differences between the simulation with and without the source can be expressed as follows.

$$\begin{cases} \Delta\varphi^-_{\text{cov}} = \left|\varphi^-_{\text{cov}}\right| - \left|\varphi^{-\,*}_{\text{cov}}\right| \\ \Delta\varphi^+_{\text{cov}} = \left|\varphi^+_{\text{cov}}\right| - \left|\varphi^{+\,*}_{\text{cov}}\right| \end{cases}$$

Finally the exploited capacity is defined as:

$$\Pi_{EXP} = \Delta\varphi^-_{\text{cov}} - \Delta\varphi^+_{\text{cov}}$$

The exploitation rate is the ratio between the exploited capacity and the coincident capacity at the scale of each wall.

$$Exp_{rate} = \frac{\Pi_{EXP}}{\Pi_{COINC}}$$

The coverage rate is defined as the ratio between the exploited capacity multiplied by the wall's surface and the energy need of the area.

$$Cov_{rate} = \frac{\Pi_{EXP}.S}{Q^*_{\text{cov}}}$$

Indicators of generation

The generated needs is the resource's quantity that is actually used by the wall to generate the area's energy needs opposite to the source. The formulae are based on the same scheme as for the exploited capacity but the flow taken into account is proportional to the difference between the wall's temperature and the comfort's temperature for which the needs, likely to be generated by the resource, are calculated. Considering φ_{gen} this flow.

$$\varphi_{gen} = \begin{vmatrix} h\,(T_w - T_{c,gen}) + \phi_{trans} & if \quad \left|Q^*_{gen}\right| > 0 \\ 0 \quad otherwise & \end{vmatrix}$$

Whether φ_{gen} contributes either to decrease or to increase the previous needs, it will respectively be considered φ^-_{gen} or φ^+_{gen}.

$$\begin{cases} \varphi^-_{gen} = \begin{vmatrix} \varphi_{gen} \quad if \quad \varphi_{gen}.Q^*_{gen} > 0 \\ 0 \quad otherwise \end{vmatrix} \\ \varphi^+_{gen} = \begin{vmatrix} \varphi_{\text{cov}} \quad if \quad \varphi_{gen}.Q^*_{gen} < 0 \\ 0 \quad otherwise \end{vmatrix} \end{cases}$$

The resource has a dual-effect upon φ_{gen}. It decreases φ^-_{gen} and increases φ^+_{gen}. The flows' differences between the simulation with and without the source can be expressed as follows.

$$\begin{cases} \Delta\varphi^-_{gen} = \left|\varphi^-_{gen}\right| - \left|\varphi^{-\,*}_{gen}\right| \\ \Delta\varphi^+_{\text{cov}} = \left|\varphi^+_{gen}\right| - \left|\varphi^{+\,*}_{gen}\right| \end{cases}$$

Finally the generated needs are defined as:

$$\Pi_{GEN} = \Delta\varphi^+_{gen} - \Delta\varphi^-_{gen}$$

It is very interesting to compare the exploited potential and the generated needs to see if the resource has a positive or negative impact on the building's comfort through the considered wall. Considering $\Pi_{EXP,net}$ this quantity.

$$\Pi_{EXP,net} = \Pi_{EXP} - \Pi_{GEN}$$

Results

We have previously shown that the low-insulated building was needing a deeper study concerning each of its walls to determine which of them were better exploiting the sun capacity than the others. As far as it concerns the low-insulated building, the results for the sun are comparable from one floor to the other so the results presented here only show the ground floor.

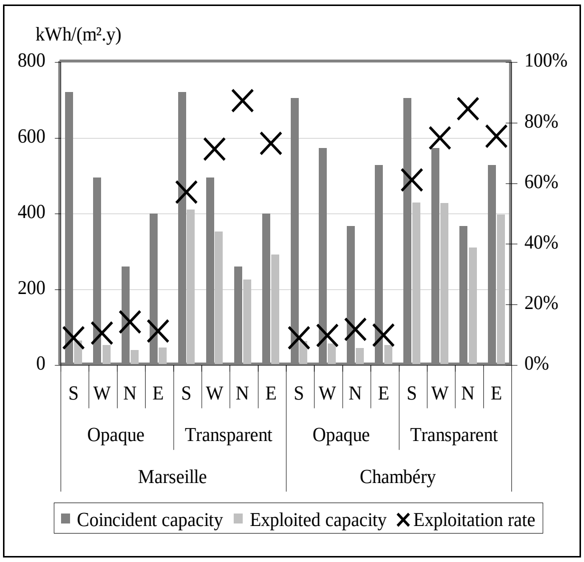

Figure 6: Solar indicators at the scale of each wall for the low-insulated building

For a given area and a given orientation, the coincident solar capacity of the opaque and transparent walls is the same, but there is a gap between the exploited capacity of the opaque (Op.) and transparent (Tr.) walls. Whatever the climate, the solar exploitation rate of the opaque walls is very low and does not differ from one wall to another. On the contrary, the exploitation rate of the transparent wall is much higher and Figure 6 shows that the windows which have the lowest coincident capacity are those which exploit it the best, with a maximum for the north orientation between 80% and 90%.

Table 6: Capacity and performance sky's indicators at the scale of each wall in Marseille

Insulation level	Type of wall	Orientation	Coincident capacity	Exploited capacity	Exploitation rate	Net exploited capacity
High	Op.	South	161.1	1.9	1%	1.8
		West	165.0	1.9	1%	1.8
		North	131.7	1.9	1%	1.9
		East	142.3	1.9	1%	1.8
	Tr.	South	120.3	6.6	5%	6.6
		West	131.7	6.6	5%	6.5
		North	115.4	6.6	6%	6.6
		East	120.0	6.6	6%	6.6
Low	Op.	South	62.4	5.7	9%	-7.6
		West	71.4	5.7	8%	-7.6
		North	53.2	5.7	11%	-7.6
		East	55.5	5.7	10%	-7.6
	Tr.	South	41.7	6.5	16%	-9.4
		West	45.4	6.5	14%	-9.4
		North	41.6	6.5	16%	-9.4
		East	41.9	6.5	15%	-9.4

Table 6 shows that the sky has a very little influence over the building's walls even if the coincident capacity is quite high for the high-insulated building, especially in Marseille. However the low-insulated walls have a much higher exploitation rate than the high-insulated walls. Even if the coincident capacity differs from one orientation to another and from one type of wall to another, no real trend comes out.

Since the exploitation rate of the opaque walls were very low, we have modelled the low-insulated building renovated with a Trombe's wall (Tw), composed of a single-glass and a 10cm-wide static air layer. The results are presented in Table 7.

Table 7: Solar performance indicators at the scale of each wall for the low-insulated building with and without a Trombe's wall.

Climate	Orientation	Retrofitting	Exploitation rate	Coverage rate	Net exploited capacity
Chambéry	*South*	Null	9%	3%	45.2
		Tw	32%	14%	102.7
	West	Null	9%	3%	35.7
		Tw	37%	17%	71.2
	North	Null	11%	4%	27.9
		Tw	47%	19%	65.6
	East	Null	10%	3%	36.3
		Tw	38%	16%	79.0
Marseille	*South*	Null	9%	5%	25.6
		Tw	31%	22%	52.0
	West	Null	10%	5%	9.4
		Tw	39%	25%	-7.7
	North	Null	14%	5%	7.1
		Tw	58%	26%	7.6

East	Null	11%	5%	11.2
	Tw	43%	22%	3.6

Table 7 shows that the Trombe's wall is a good solution since it increases the exploitation rate. It is interesting to notice that the solar capacity is better exploited on the north orientation than the others, just like the windows. It comes out that the net exploitation of the sun by the Trombe's wall is better in Chambéry where it increases for each orientation whereas in Marseille it increases only for the south orientation. It also appears that the net exploited capacity is negative on the west orientation in Marseille which implies that the Trombe's wall generate more needs than it covers. It indicates that the technology can be optimized thanks to the analysis of the performance indicators at each time step.

CONCLUSION

Considering the heating needs, the indicators show that the sun could easily cover the residual thermal needs of the high-insulated building, and the thermal needs of the low-insulated building could largely be covered with an appropriate system management. The energy sinks' capacity is large enough to cover the cooling needs in each case but the sky is not exploited at all by the current technologies. It also comes out that the existing opaque walls are not designed to exploit the sources of the environement. Thus, the next step is an optimization analysis which should entitle us to find the wall's characteristics that would maximize the performance indicators. This work will be carried out in the next months in order to hilight the relevance of the indicators defined in this paper.

ACKNOWLEDGEMENT

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NOMENCLATURE

Symbols

T temperature, K

Q energy needs, kW

S surface, m²

F shape factor

V volume, m^3

C_p specific heat capacity of air, J/(K.kg)

$\dot{m}$ mass flow rate, kg/s

Greek letters

Π capacity, W

Φ incident solar radiation , W

ρ density, kg/m^3

φ energy flow rate, W/m²

τ_{ventil} air change rate, vol/h

Index / Exponents

c comfort

gen generated

cov covered

out outside air

in inside air

w wall

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