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Liquisol
Wiser with Energy

Welcome to the 4EVER simulation tool.

At Liquisol, we ordered a software simulation tool at the Belgian university KU Leuven based on the Fraunhofer test reports of 4EVERblue and 4EVERdark.

This document describes the process on how to obtain the results.

The following parameters are set in the online version:

- Temperature regime = T2 = upper temperature boundary set to 25 ℃
- Air infiltration = A3 = 1,5 m^3/m^2 per hour.
- The Energy Efficiency Ratio of the airconditioning system is set to 1,5.
- Electricity cost was found on the European Union website.
- greenhouse gas emissions CO_2 on the European Union website.

If you request a simulation using other setpoints, then please contact us. We would be delighted to help you pre-calculate the impact of our energy saving coatings on your building.

For more questions or remarks, please also mail to info.factory@liquisol.com.

Success with your energy-saving project.

Tom Huysmans

KU LEUVEN

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LEUVEN 26/05/2021

Calculation of energy savings when applying 4EVERblue and 4EVERdark top coatings on skylights in warehouses

Contents

1. Introduction

The Liquisol company requested the Building Physics and Sustainable Design section of KU Leuven to conduct a study in order to determine the energy savings and comfort improvement in warehouses when 4EVERblue and 4EVERdark coatings are applied as top coatings on skylights. The assessment was performed by means of annual energy simulations calculating the hourly heating and cooling demand, and overheating hours (in cases when cooling is disabled). When performing the analysis, the following parameters, defining the warehouse envelope, indoor and outdoor environment, were modified:

- five envelope variants (E1, E2, E3, E4, E5)
- two temperature regimes (T1, T2)
- three air exchange rates (A1, A3, A3)
- three skylight-to-roof ratios (5%, 10%, 15%)
- three skylight top coatings (clear, 4EVERblue, 4EVERdark)
- and five different climates (London, Madrid, Nancy, Prague, Riyadh)

For the resulting 1360 variations, heating and cooling demand are presented in kWh/m² per year together with the difference (%) between the same models with different top coatings. Moreover, as an informative addition, results are also expressed as the carbon footprint, in tons of CO_2 per year. In this report, first, an overview of the simulated variations is given, then the calculation is presented on several examples. In the end, the results are discussed and followed by a detailed explanation of the created calculation tool.

**This study is comparable to the study conducted for the estimation of energy savings with the 2WHITE coating (available only in Dutch) as several simulation parameters were replicated.*

2. Simulations

2.1. Geometry and envelope of the warehouse

All the simulations are performed on a unique warehouse size. The observed warehouse has an area of 2500 m² (50 x 50 m) and a height of 6 m, resulting in a total volume of 15000 m³ and an envelope of 6200 m². This volume is modelled as a single air zone, however, both internal walls and stored goods capacitance are taken into account. It is assumed that the warehouse has 4 internal partition walls (4 x 6 x 50 m) that traverse the indoor space, resulting in the additional surface of 1200 m². The additional thermal mass attributable to the stored goods is arbitrary assumed to increase the capacitance with a factor of 10 compared to the air alone.

Table 1 provides an overview of the considered five different insulation qualities of the warehouse envelope. The investigated variations include: an uninsulated envelope, two variations of a lightweight building envelope (5 and 10 cm of insulation) and two variations of a heavyweight building envelope (5 and 10 cm of insulation). The uninsulated envelope (E1) consists entirely of concrete slabs. In the lightweight envelope variants (E2 and E3), the walls and roof are made of sandwich panels and the concrete floor is insulated. Finally, in the heavyweight envelopes (E4 and E5), the floor and the walls are constructed from insulated concrete slabs, while the roof consists of sandwich panels.

Table 1 Five variants of the building envelope of the warehouse including total thickness d and the U-value as well as the equivalent U-value for the floor calculated according to [5].

ID	Walls	Floor	Roof
E1	Aerated concrete slabs d = 17.5 cm U = 0.60 W/(m²K)	Reinforced concrete d = 15 cm U_{eq} = 0.80 W/(m²K)	Aerated concrete slabs d = 24 cm U = 0.44 W/(m²K)
E2	Sandwich panel (PUR-core and metal finish) d = 8.4 cm U = 0.38 W/(m²K)	Reinforced concrete, insulated with 5 cm PUR d = 20 cm U_{eq} = 0.35 W/(m²K)	Sandwich panel (PUR-core and metal finish) d = 8.4 cm U = 0.38 W/(m²K)
E3	Sandwich panel (PUR-core and metal finish) d = 13.8 cm U = 0.19 W/(m²K)	Reinforced concrete, insulated with 10 cm PUR d = 25 cm U_{eq} = 0.22 W/(m²K)	Sandwich panel (PUR-core and metal finish) d = 13.8 cm U = 0.19 W/(m²K)
E4	Prefab. concrete panel (PUR-core between 2 concrete slabs) d = 20 cm U = 0.50 W/(m²K)	Reinforced concrete, insulated with 5 cm PUR d = 20 cm U_{eq} = 0.35 W/(m²K)	Sandwich panel (PUR-core and metal finish) d = 8.4 cm U = 0.38 W/(m²K)
E5	Prefab. concrete panel (PUR-core between 2 concrete slabs) d = 25 cm U = 0.32 W/(m²K)	Reinforced concrete, insulated with 10 cm PUR d = 25 cm U_{eq} = 0.22 W/(m²K)	Sandwich panel (PUR-core and metal finish) d = 13.8 cm U = 0.19 W/(m²K)

In addition to these five building envelope variants, the influence of skylights on the roof is assessed. In total, three alternatives of the transparent area size are observed and the total glazing to roof ratio varies from 5% to 10% and 15%. The optical properties of the opaque roof area are constant, and an EPDM layer as the finishing coat is assumed for all cases. The emission factor of the EPDM coat is set to 0.86 and the reflection factor is equal to 0.06, which means the absorption factor is equal to 0.94 (see [1] and [4]).

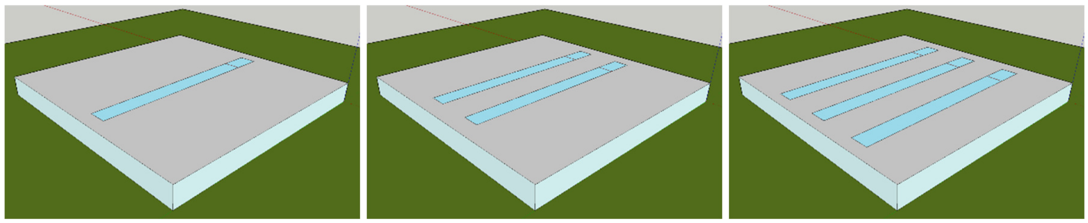


Figure 1 Display of the size variation of the glazed roof area, respectively 5%, 10% and 15%.

Together with the glazing area also the glazing properties, specifically the glazing top coating, were alternated. To assess the energy savings and improvements in comfort due to the 4EVERblue and 4EVERdark coating, the clear glazing option was selected as the base case. The properties of the clear glazing resemble the Makrolon polycarbonate glazing material with 16 mm thickness [6]. For the proposed assessment the total energy transmission (i.e. g-value) was adjusted to represent the selected top coatings while the thermal transmittance (i.e. U-value) of all glazing components remained the same. The different glazing properties used in the simulation can be found in Table 2.

Table 2 Properties of the glazing with no coat, 4EVERblue and 4EVERdark top coating.

ID	Top coating	U-value [W/m^{2}K]	g-value [%]	TSER
clear	Clear	2.8	0.7	30%
blue	4EVERblue	2.8	0.43	57%
dark	4EVERdark	2.8	0.35	65%

The convective heat transfer coefficients for different envelope elements are selected according to the ISO 6946:2007 – Annex A standard [3], and are the following:

On the inside:

- 5 W/m^{2}K for heat flow upwards → 18 kJ/hm^{2}K
- 2.5 W/m^{2}K for horizontal heat flow → 9 kJ/hm^{2}K
- 0.7 W/m^{2}K for downward heat flow → 2.5 kJ/hm^{2}K

On the outside:

- 4 + 4*v W/m^{2}K with v as the wind speed
  For an average wind speed of 3.5 m/s → 64 kJ/hm^{2}K
- Ground → 9999 kJ/hm^{2}K

2.2. Indoor climate

Two variants of the indoor climate temperature boundaries are proposed for the calculation. The first option represents a low comfort level where the heating setpoint is 16°C and the cooling setpoint is 28°C. The second option represents an increased comfort level where the heating temperature is set at 19°C and the cooling temperature at 25°C. For both options, the heating and cooling demand were calculated, as well as the overheating temperature and number of hours outside the upper temperature boundary when cooling is disabled.

Table 3 Variations of indoor temperature setpoints for heating and cooling.

ID	Comfort level	Lower temperature boundary	Upper temperature boundary
T1	Low	16°C	28°C
T2	High	19°C	25°C

Furthermore, the calculations are performed for three values of the infiltration flow rate; 6, 3 and 1.5 m^3/h per square meter of floor area. Since the infiltration rate, number of air exchanges of the internal volume per hour (ACH), depends on the total indoor volume and floor area both values are shown in Table 4.

Table 4 Variations of infiltration air exchange rates.

ID	Flow rate [m^3/m^2 per hour]	ACH [1/h]
A1	6	1
A2	3	0.5
A3	1.5	0.25

The last parameter, assumed in these simulations, that influences the indoor climate is the internal gains. Since no additional information is given about the equipment installed in the observed warehouse, only lighting gains are taken into account. For the lighting gains a value of 3 W/m^2 is assumed according to the NBN EN 13779:2004 standard [2] (pages 24-25).

2.3. Outdoor climate

For conducting this study five cities, representing different climates and countries, are selected. All simulations are performed for each of the following proposed climates:

1. United Kingdom London
2. Spain Madrid
3. France Nancy
4. Czech Republic Prague
5. Saudi Arabia Riyadh

The selected cities are indicated on a climatic map presented in Figure 2.

Figure 2 Cities an climates selected for conducting the study.

In addition to the weather data for each case, the ground temperature is introduced to better characterize the heat losses to the ground. For all soils, the following properties are selected: thermal conductivity of 12.2 kJ/(hmK), a density of 2650 kg/m^3 and a specific heat capacity of 0.85 kJ/(kgK). The ground temperature is approximated with a sinusoidal model as a function of the time of the year and included in the simulation as a boundary condition at the depth of 0.5 m below the floor level. Moreover, the correlation with the outdoor temperature is also taken into account with a delay of 30 days due to the ground inertia. The fluctuation of the ground temperature is shown in Figure 3.

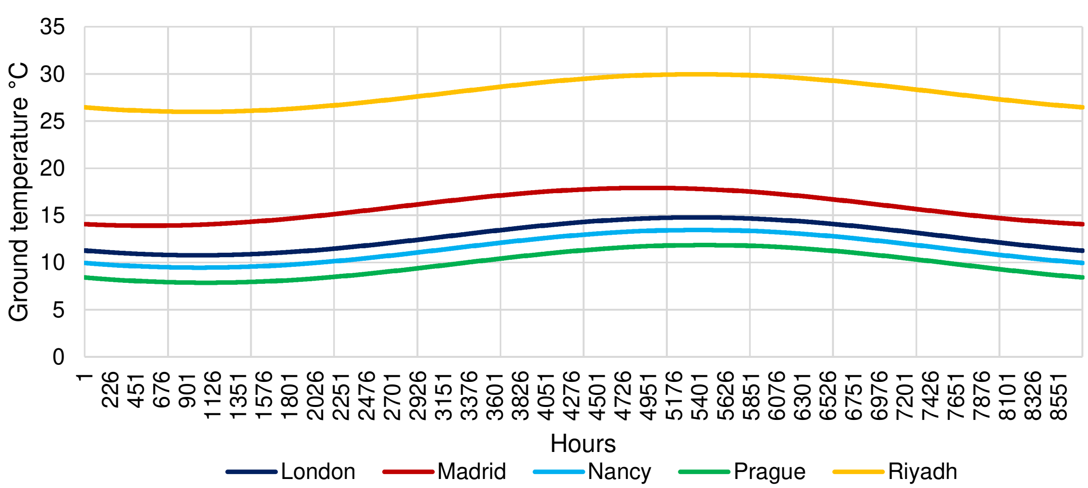


Figure 3 Yearly ground temperature fluctuation for the observed climates.

2.4. Resulting building models

To enable systematic organization of the simulations code names were assigned to each model in the following manner:

$$\underbrace{\mathrm{E1}}_{\text{Envelope ID}} - \underbrace{\mathrm{T1}}_{\text{Setpoint ID}} - \underbrace{\mathrm{A1}}_{\text{Air infiltration ID}} - \underbrace{05}_{\text{\% of glazing}} \underbrace{\mathrm{blue}}_{\text{Coat ID}} - \underbrace{\mathrm{c}}_{\text{Simulation type}}$$

The meaning of different IDs is indicated in the tables in sections 2.1. and 2.2., while the simulation type indicates whether the simulation was performed with enabled cooling (c), or assuming overheating is occurring (oh). Each of the building models is simulated in all five climates, which is not indicated by the code names.

3. Example of the performed analysis

3.1. Impact of selected parameters

In this section, an example of the performed calculations is shown through a sensitivity analysis. The sensitivity analysis is presented on the base model (*E3-T1-A2-10clear-c*) located in Madrid. In total 11 variations, in which one parameter is changed from the base model each time, are shown in Table 5.

Table 5 Summary of the variations presented on one example in the Madrid climate.

Variation	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Envelope	E3	E1	E2	E4	E5	E3	E3	E3	E3	E3	E3	E3
Setpoint	T1	T1	T1	T1	T1	T2	T1	T1	T1	T1	T1	T1
Infiltration	A2	A2	A2	A2	A2	A2	A1	A3	A2	A2	A2	A2
Transparent roof area [%]	10	10	10	10	10	10	10	10	5	15	10	10
Top coat	clear	clear	clear	clear	clear	clear	clear	clear	clear	clear	blue	dark
Q_{heat} [kWh/m²]	32	51	43	35	27	55	69	16	32	33	38	40
Q_{cool} [kWh/m²]	32	1	30	24	29	50	28	38	12	57	15	11
$T_{overheating}$ [h]	2425	208	1917	2229	2635	3361	1576	3232	1608	2981	1619	1327

A short interpretation of the results follows for each variation:

1. When changing the envelope from a lightweight insulated one to an uninsulated envelope the heat exchange with the ambient significantly increases. This, therefore, increases the heating demand and significantly decreases the cooling demand together with the potential overheating hours.

2. When changing the envelope from a lightweight with 10 cm insulation to the one with 5 cm insulation, the heat exchange with the ambient slightly increases. Here the heating demand is moderately increased while the cooling demand shows a smaller difference. The overheating hours decrease.

3. When changing the envelope from a lightweight with 10 cm insulation to a heavyweight with 5 cm insulation the thermal inertia of the building increases while the insulation quality decreases. That results in a slightly increased heating demand while the cooling demand shows a moderate difference. The overheating hours slightly decrease.

4. When changing the envelope from a lightweight with 10 cm insulation to a heavyweight with 10 cm insulation the effect of the thermal inertia of the building increases which results in a slight decrease of both heating and cooling demand while the overheating hours increase.

5. With the change of the setpoint from a low-comfort indoor climate to a higher comfort both heating and cooling demand increase. The overheating hours mainly increase because of the lowering of the upper temperature boundary from 28°C to 25°C.

6. When doubling the air infiltration rate the heating demand increases due to the increased amount of cold air entering the space in the winter months. The same effect, natural ventilation, helps keeping the indoor climate at a lower temperature in summer months, therefore the cooling demand and overheating hours decrease.

7. In case when the air infiltration rate decreases by half, the heating energy demand decreases since there is a lower exchange of cold air in the winter. On the other hand, in the summer months, the energy demand increases, together with a significant rise of overheating hours due to a lack of natural ventilation.

8. When the glazing to roof ratio is decreased to 5% direct solar gains are less pronounced in the energy balance. This effect does not affect the heating demand as much as the cooling demand and overheating hours, which significantly decrease.

9. In case when the glazing to roof ratio is increased to 15% direct solar gains are more pronounced in the energy balance. This effect does not affect the heating demand as much as the cooling demand and overheating hours, which significantly increase.

10. When the 4EVERblue coat is applied as the top coating on the skylights the total solar energy transmission is lower than in the case when the glazing is clear. This results in higher energy demand for heating because solar gains contribute to the total heat input in the energy balance. However, the drop in solar gains (dominant in summer months) facilitates the operation of the cooling system, resulting in lower energy demand. The same is noticeable for the decrease in overheating hours.

11. When the 4EVERdark coat is applied as the top coating on the skylights the total solar energy transmission is even lower than in the case when 4EVERblue is applied. This results in a very low cooling demand, and a slightly higher heating demand compared to the 4EVERblue coating. The overheating hours in this case also decrease.

It is important to mention that, due to the different weather conditions (mainly outdoor temperature and solar radiation), these relations will be different for different climates. The impact of each of the parameters shown as percentual deviation from the base model is shown in the following diagrams.

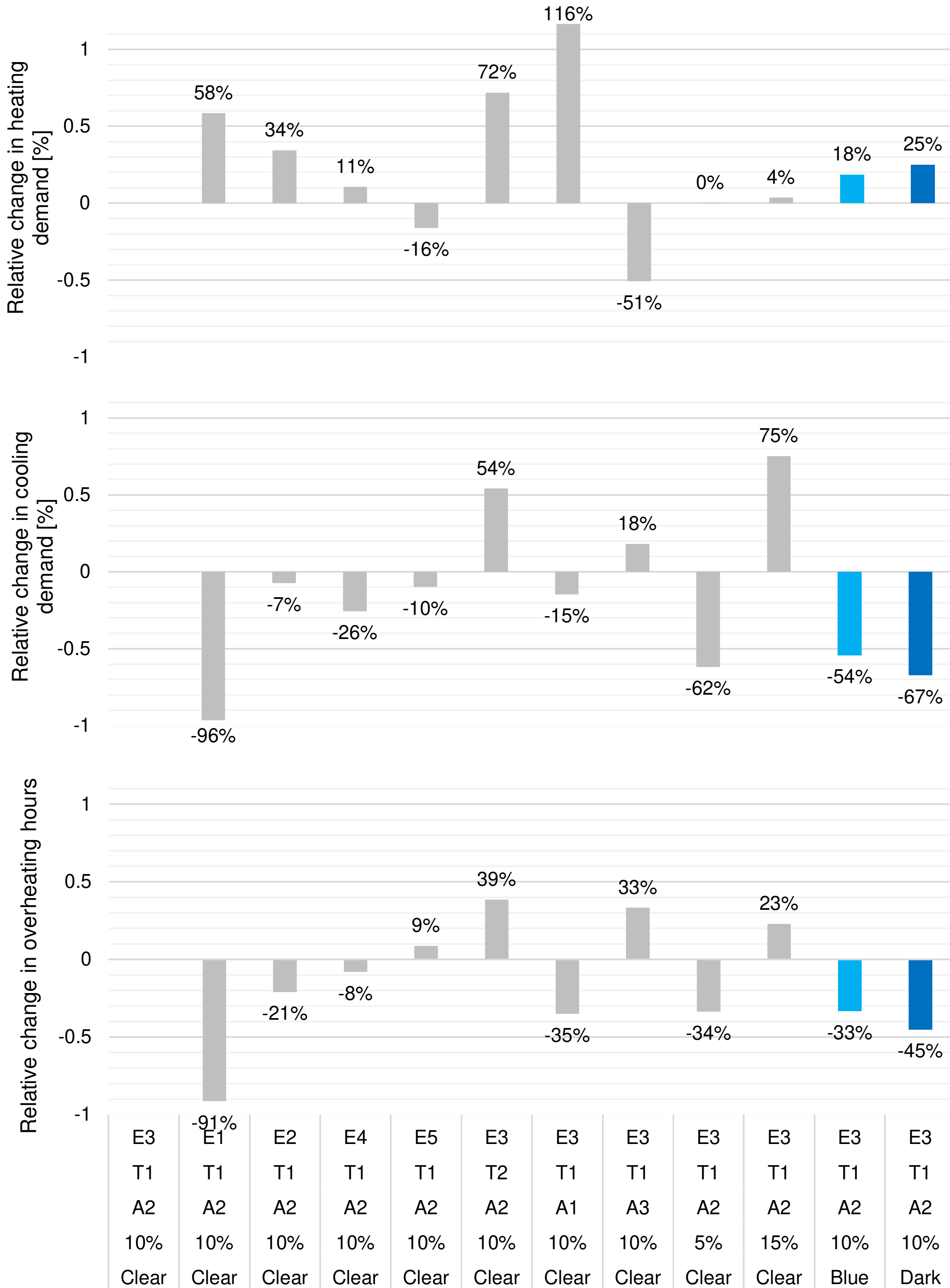


Figure 4 Sensitivity analysis shown for one example in the Madrid climate.

3.2. Impact of different climates

In the next step, the same building shell is allocated in different climates. The base for the comparison is the model *E3-T1-A2-10* (same as in 3.1.). For each climate, the simulation results for the three different skylight top coatings (clear, 4EVERblue and 4EVERdark) are shown, while transparent roof area is equivalent in all the cases. This way, it is possible to visualize the immediate effect of the three types of finishes on the achieved indoor temperature and energy demand. The results (Figure 5 to Figure 9) are presented for a summer week in each climate since the savings in cooling are the focus of interest in this study.

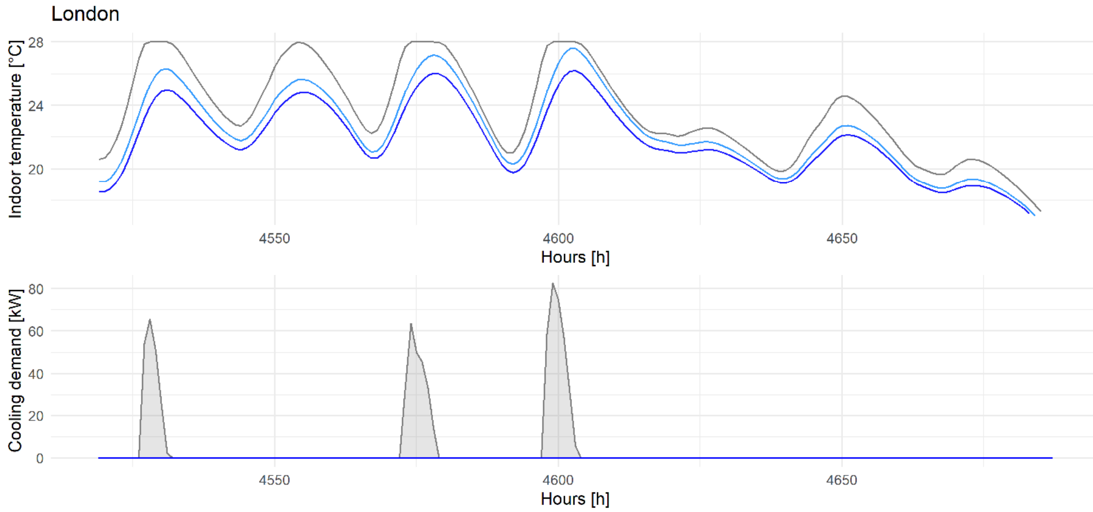


Figure 5 Simulated indoor temperature and cooling demand for a summer week in London. The grey colour represents the clear, the light blue represents the 4EVERblue and the dark blue represents the 4EVERdark skylight coating.

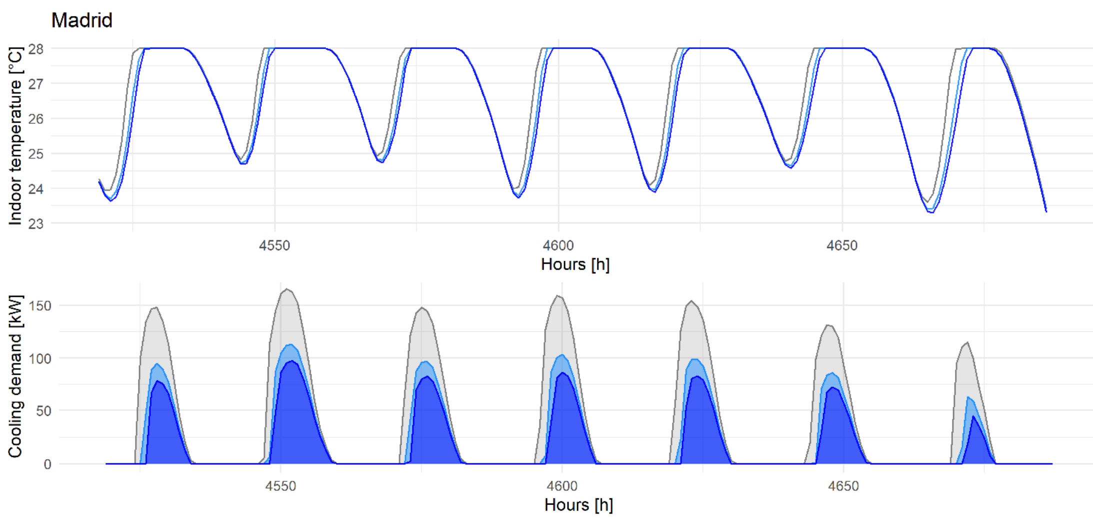


Figure 6 Simulated indoor temperature and cooling demand for a summer week in Madrid. The grey colour represents the clear, the light blue represents the 4EVERblue and the dark blue represents the 4EVERdark skylight coating.

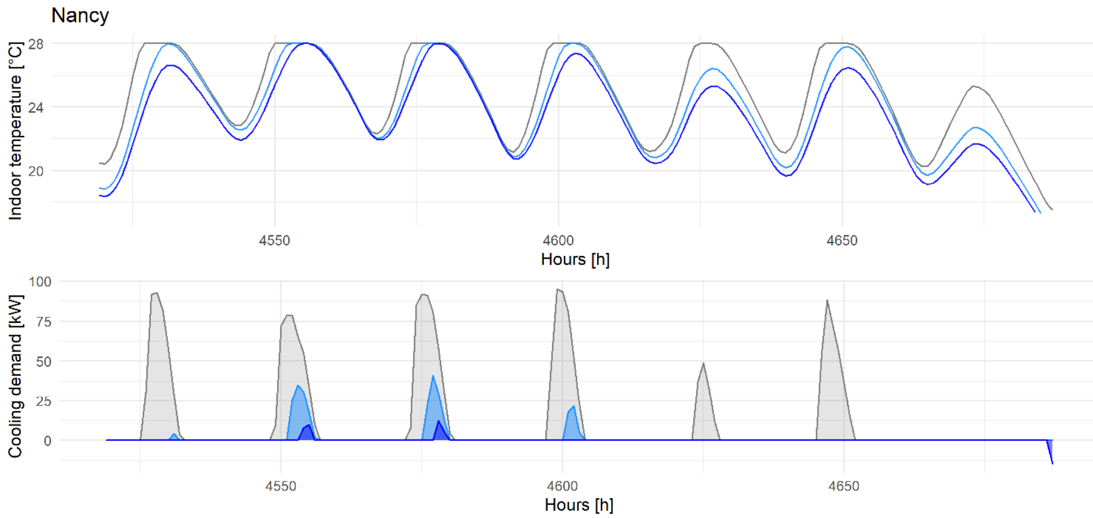


Figure 7 Simulated indoor temperature and cooling demand for a summer week in Nancy. The grey colour represents the clear, the light blue represents the 4EVERblue and the dark blue represents the 4EVERdark skylight coating.

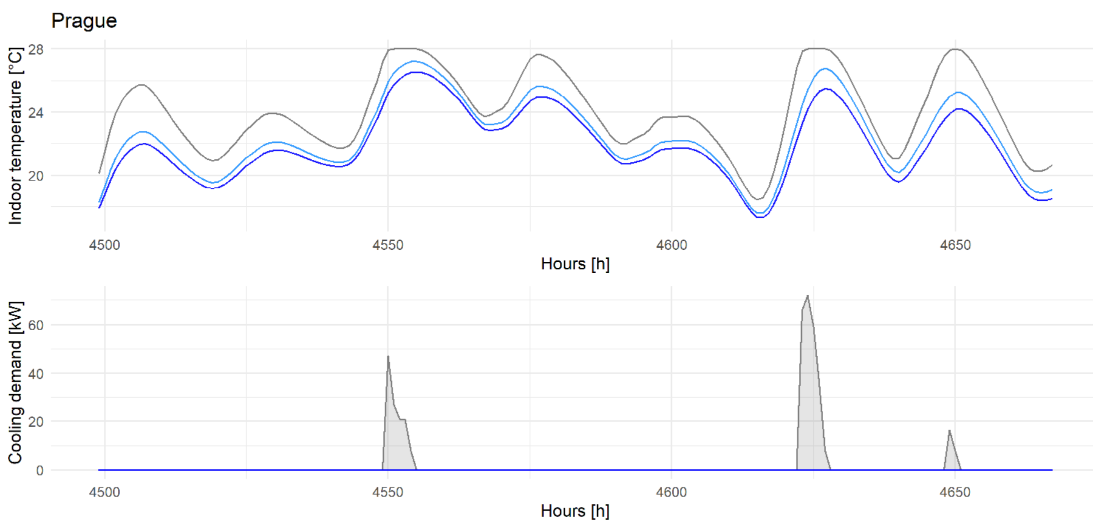


Figure 8 Simulated indoor temperature and cooling demand for a summer week in Prague. The grey colour represents the clear, the light blue represents the 4EVERblue and the dark blue represents the 4EVERdark skylight coating.

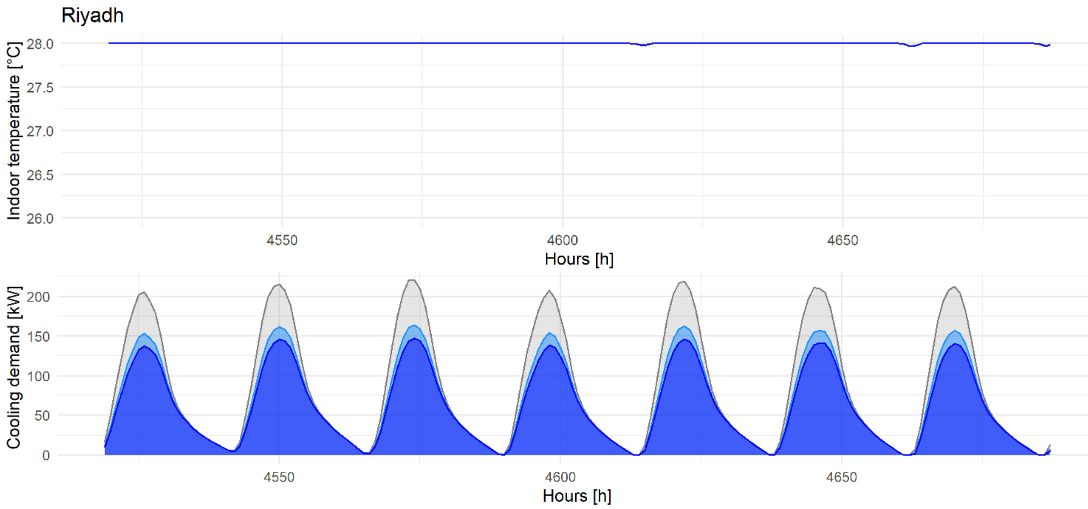


Figure 9 Simulated indoor temperature and cooling demand for a summer week in Riyadh. The grey colour represents the clear, the light blue represents the 4EVERblue and the dark blue represents the 4EVERdark skylight coating.

From the presented plots it is possible to distinguish three advantages of the application of the 4EVERblue and 4EVERdark coatings compared to skylights with no coating. First, the indoor climate keeps a better comfort level (i.e. lower air temperature), which is particularly pronounced in mild climates (London, Nancy and Prague). For the observed cases, the application 4EVERblue results in up to 4.5°C lower temperatures, while 4EVERdark results in up to 5.8°C lower temperatures. Secondly, the cooling demand, shown as the shaded area in the presented diagrams, decreases. Finally, together with the cooling demand also the required installed power of the cooling system can be decreased. Figure 10 shows the yearly heating and cooling energy demand, per square meter of the warehouse, corresponding to the presented examples.

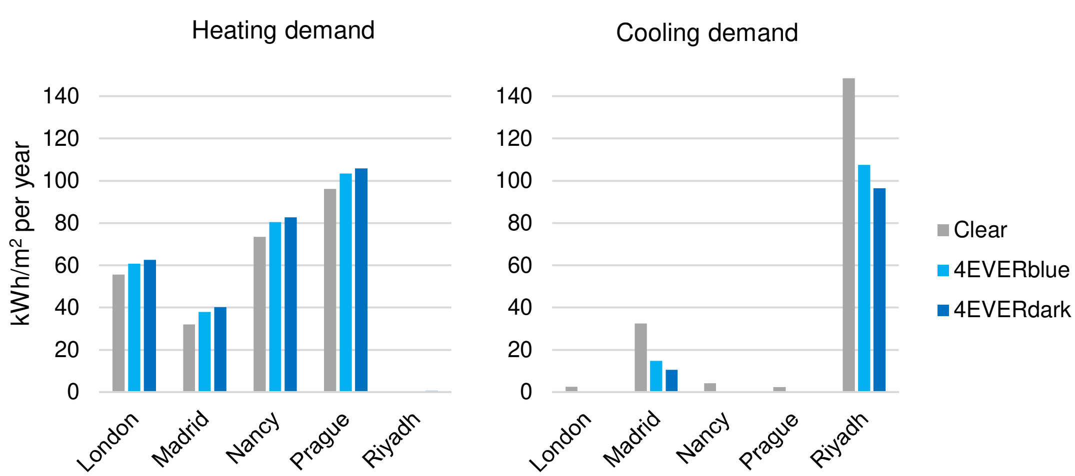


Figure 10 Yearly heating and cooling energy demand per square meter for the first examples.

3.3. Impact of the glazing to roof ratio

Next, for the same base model shown in the previous section (*E3-T1-A2)*, the impact of the skylights' size is investigated. Here, both the size of the glazed area and the effect of different coats are assessed for all climates. Figure 11 shows the increase in heating demand as a function of the glazing area on the roof. It is possible to notice that the increase can be approximated with a linear function, and it is proportional to the increase in the glazed area, as the heat losses to the ambient increase. Moreover, the relative difference of the increase in the heating demand between top coatings is similar in different climates and is mainly caused by the decrease of solar gains when coatings are applied.

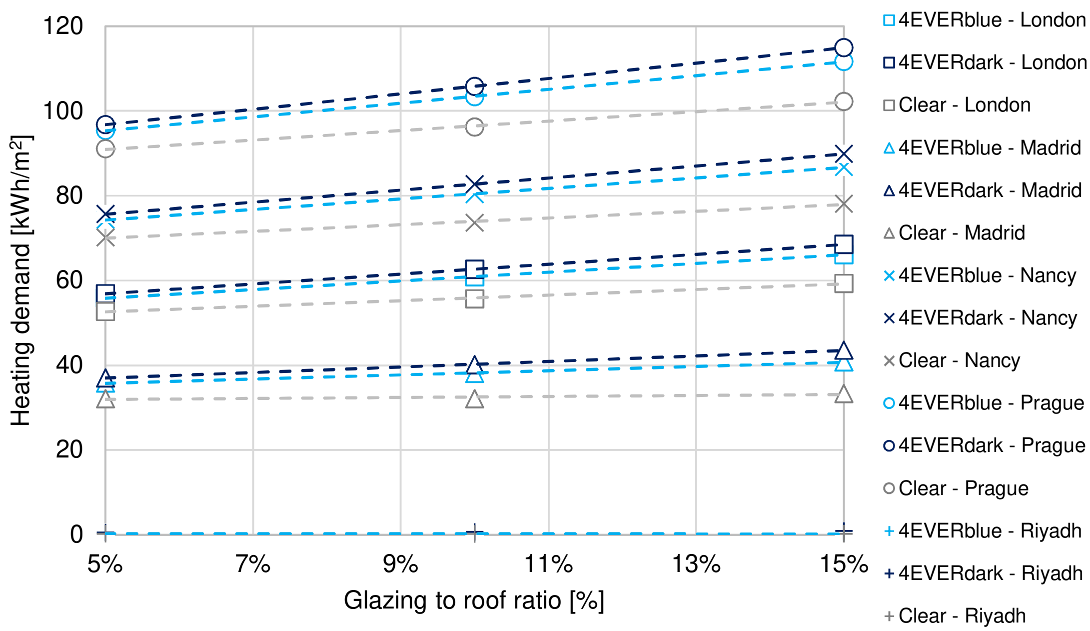


Figure 11 Comparison of the heating demand for different glazing area, top coatings and climates on one example.

The impact of the roof glazing area size on the overall yearly cooling demand is shown in Figure 12. As expected, the impact is greater for the cooling than for the heating demand. Furthermore, here the impact when no coatings are applied is more pronounced, especially for climates with high solar gains where the difference in the cooling demand can jump up to 100% for only a 10% increase in the glazed area. Contrary to the diagram shown for the heating demand, here lines significantly diverge when comparing different top coatings.

In Figure 13 the number of overheating hours during one year is shown as a function of the roof glazing area. The diagram, as expected, indicates relations similar to the ones noticed in the previous diagram for the cooling demand. From both Figure 12 and Figure 13, it is possible to conclude that, when top coatings are applied in mild climates (London, Nancy, Prague), the increase in glazing area does not produce a significant increase in cooling demand and overheating hours. On the other hand, when only clear glazing is applied, the relation is more pronounced.

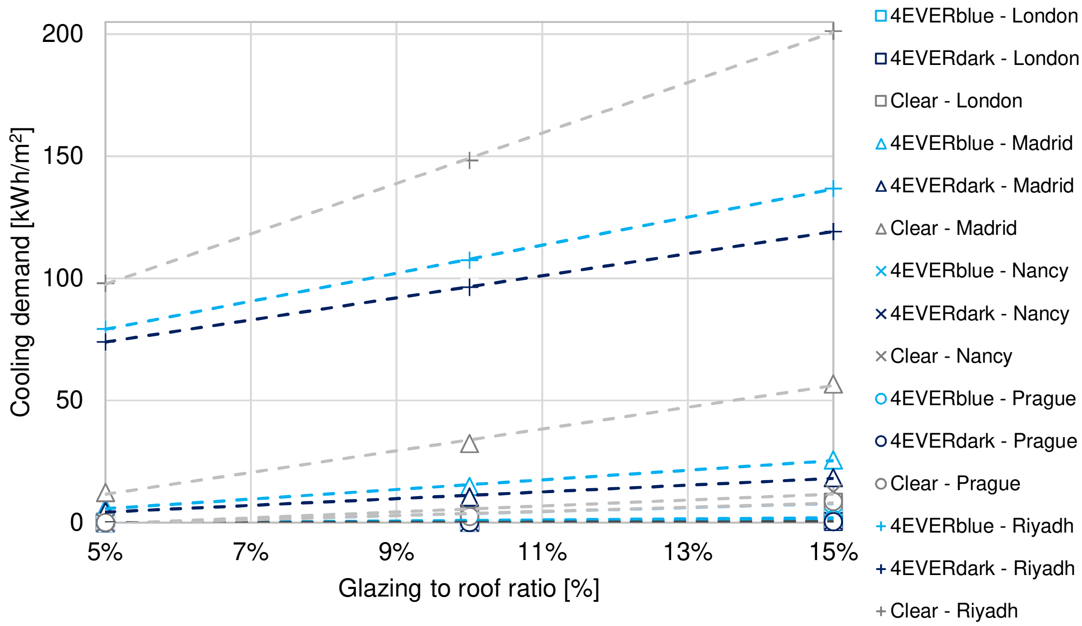


Figure 12 Comparison of the cooling demand for different glazing area, top coatings and climates on one example.

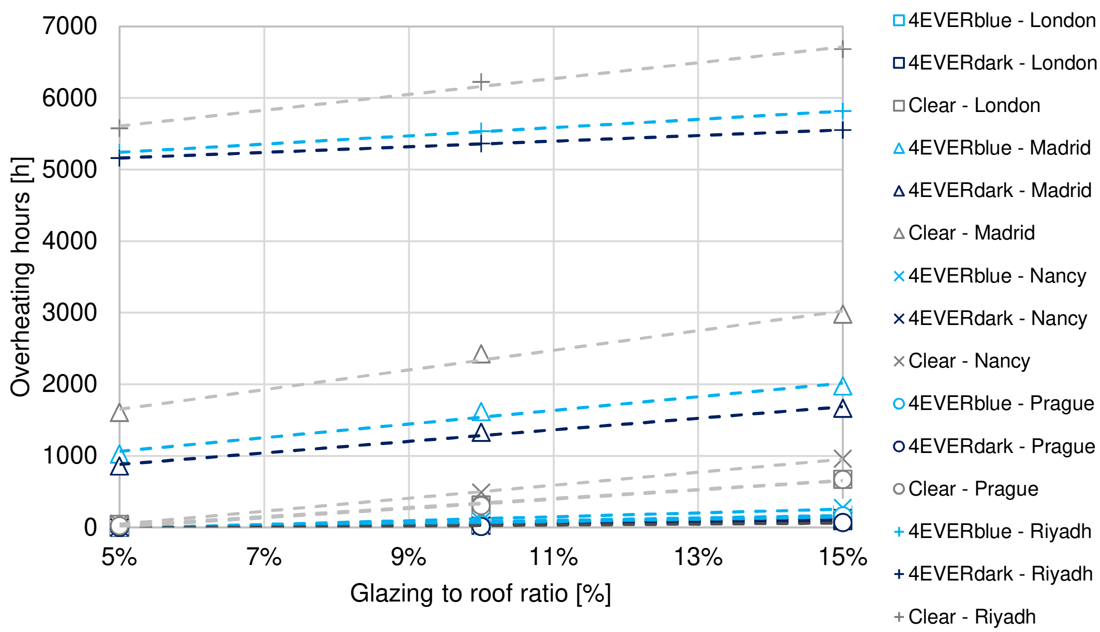


Figure 13 Comparison of the overheating hours for different glazing area, top coatings and climates on one example.

4. Results

In this chapter, the results, previously presented only as an example, are shown for all performed simulations. Impact analysis of different parameters is carried out focusing mainly on the glazing top coatings, the glazing to roof ratio and the indoor climate comfort. In the following discussion, results are presented with boxplots that represent the distribution of data. In all figures, results are shown as the difference of the total annual energy deviation or difference in the number of hours for the cases when 4EVERblue and 4EVERdark top coatings are applied in comparison to when no coating is applied. The shaded rectangle shows the first and third quartiles and contains 50% of the results. The median is shown as a line inside this rectangle, while the minimum and maximum results are indicated by whiskers.

Since the study is performed on various envelopes, conditions and climates, firstly general plots showing the increment in heating (Figure 15) and the savings in cooling (Figure 17) energy requirements are presented. On the left side the results are presented as percentages while on the right side of the figures, the difference in energy demand is quantified in kWh/m².

To interpret Figure 15 correctly, it is important to take into account the magnitude of the observed energy demand, and not only the relative difference. The apparently higher increment in heating demand in warm climates (Riyadh) is caused by a relatively low total demand. Thus, the required low heating demand is in some cases fully covered by solar gains, therefore the increment of 100% when solar gains are reduced by the application of top coatings. For all other cases, the increase in the heating demand is equally pronounced.

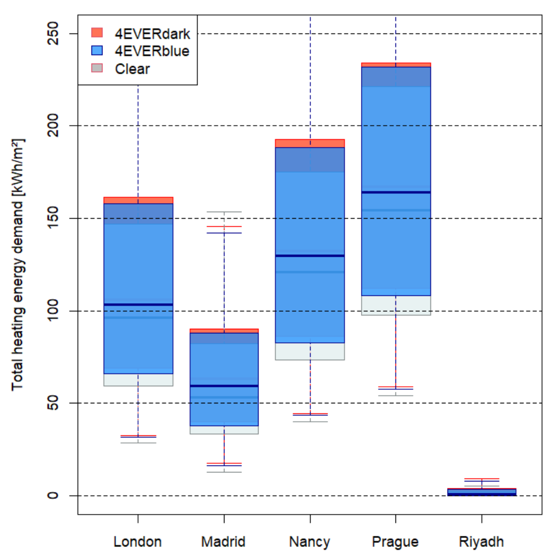


Figure 14 Total yearly heating demand in kWh/m² when comparing all three top coatings.

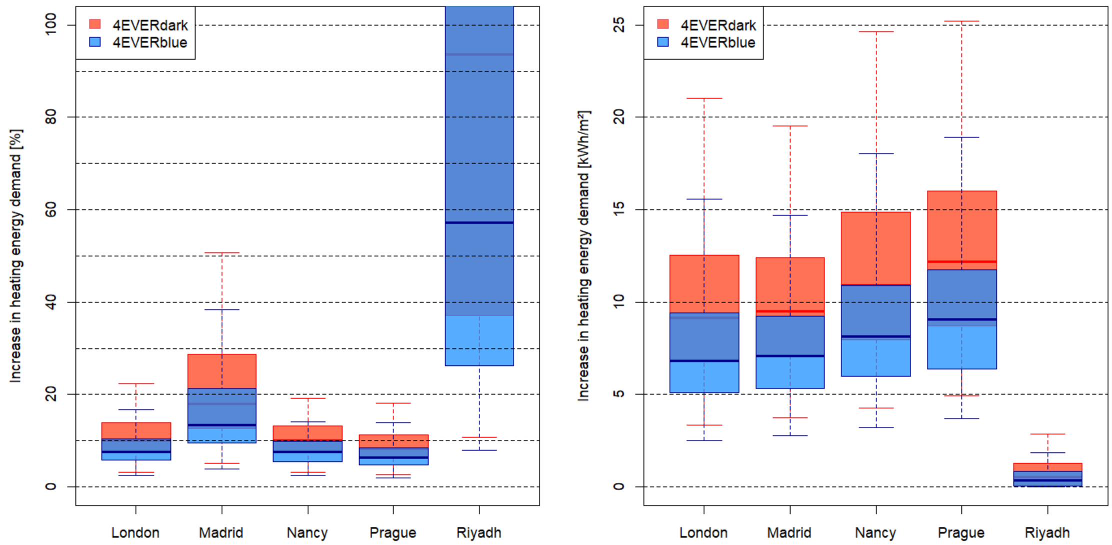


Figure 15 Increase in yearly heating demand shown as percentual deviation (left) and as the difference in kWh/m^2 (right) for all models, conditions and climates.

When observing the decrease in cooling energy demand, Figure 17, a similar effect can be noticed in the mild climates (London, Nancy, Prague). For some cases the application of the top coating on the glazed areas can fully replace the necessity of cooling systems, therefore the decrease of 100%. However, even in warmer climates (Madrid, Riyadh), it is possible to notice a significant drop in the cooling demand, which is even more impressive when presented as energy saving in kWh/m^2.

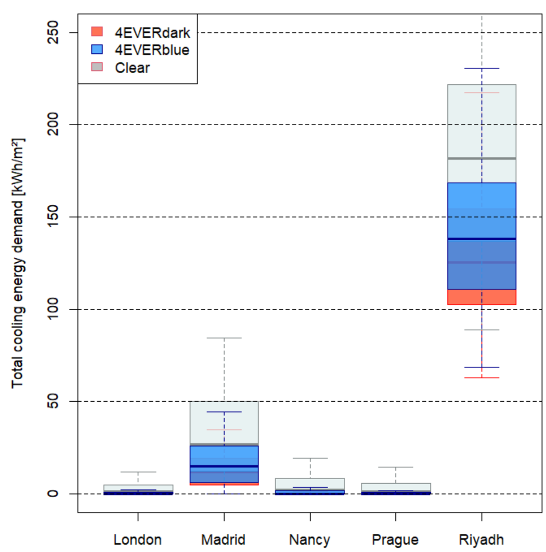


Figure 16 Total yearly cooling demand in kWh/m^2 when comparing all three top coatings.

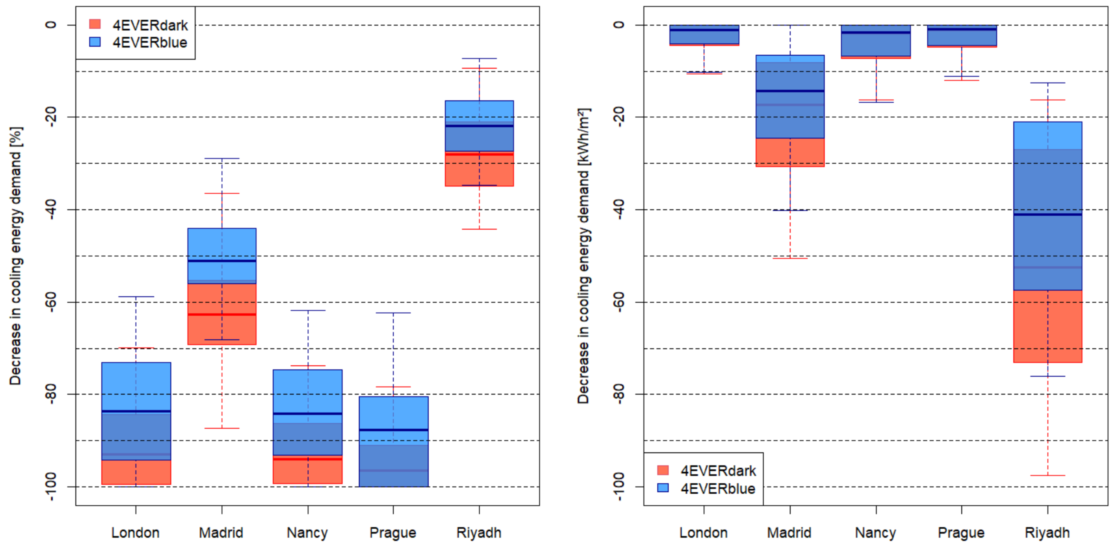


Figure 17 Decrease in yearly cooling demand shown as percentual deviation (left) and as the difference in kWh/m^2 (right) for all models, conditions and climates.

Generally, it is possible to conclude that, for very warm climates (Riyadh), the application of top coatings will have a greater positive impact on savings in the cooling season, than a negative impact causing additional consumption in the heating season. However, for other climates, it is difficult to conclude from the diagrams only. Therefore, Table 6 shows an overview of the number of cases where the increase in heating demand is greater than the decrease in cooling demand after applying top coatings.

Table 6 Cases in which the increase in heating demand is greater than the decrease in cooling demand, and cases when the cooling system becomes unnecessary due to the application of top coatings. All percentages represent the number of cases out of the total number in that climate. The values shown in brackets indicate the increase from the corresponding cases with no top coating.

	$\Delta Q_{heat} > \Delta Q_{cool}$		Cooling system unnecessary		
	4EVERblue	4EVERdark	Clear	4EVERblue	4EVERdark
London	88%	92%	19%	29% (+10%)	38% (+19%)
Madrid	22%	24%	2%	3% (+1%)	5% (+3%)
Nancy	83%	89%	22%	30% (+8%)	36% (+14%)
Prague	94%	97%	23%	45% (+22%)	52% (+29%)
Riyadh	0%	0%	0%	0% (+0%)	0% (+0%)

This effect seems to be present in the majority of cases in mild climates (London, Nancy, Prague). When creating this table the exact difference in demand was not individually examined and some of the differences may be negligible in practice, thus the table should be interpreted as “no difference or greater impact on the heating than cooling demand”. Nevertheless, other factors may influence the choice of application of the coatings. One of them might be the possibility of avoiding the cooling system installation. Table 6 also shows the increase in the number of cases that do not require cooling systems after applying 4EVERblue or 4EVERdark coatings. Furthermore, the cost or the availability of the energy required for heating can differ from the one for cooling. Finally, it is necessary to keep in mind the importance that different envelopes and internal conditions may have on the energy demand, especially the temperature setpoints which in the conducted study were the main criteria to determine whether heating and/or cooling is needed. Thus, before drawing conclusions the complete list of results (provided as an Excel document) should be consulted.

Figure 18 shows the decrease in the overheating hours when the cooling system is disabled. The overheating hours are defined as the number of hours in one year in which the achieved indoor air temperature of the warehouse exceeds the temperature of 28°C in case of regime T1 and 25°C in the case of regime T2. On the left, the total number of overheating hours is shown while on the right side the difference of overheating hours for each top coating in comparison to the corresponding cases with no coating is presented. Interestingly, the decrease in the number of overheating hours is similar in all climates, although the total number of overheating hours is much smaller in mild climates (London, Nancy, Prague).

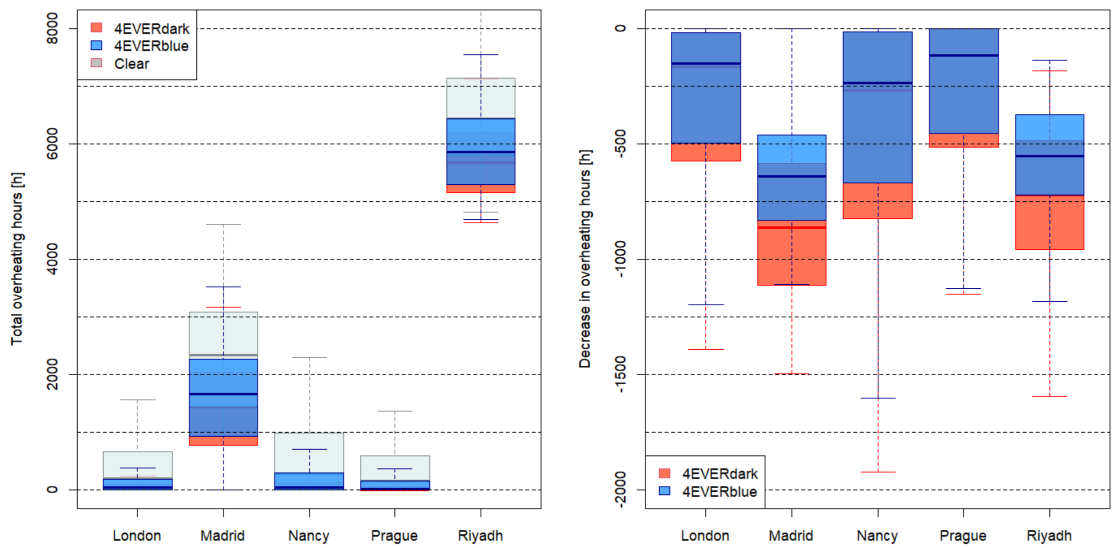


Figure 18 Overall number of overheating hours (left) and the decrease in overheating hours when applying top coatings (right) for all models, conditions and climates.

4.1. Impact of the glazing to roof ratio

In this section, the impact of the ratio of the glazed area in comparison to the total roof area is explored. Since the plots which show the percentage difference can be deceiving, here all results are presented in kWh/m^2 per year. While in section 3.3. the relations for only one example of the envelope and indoor conditions is presented, here plots include all performed simulations. However, the conclusion drawn from Figure 11 is valid also when all simulations are observed together, Figure 19. Precisely, that the impact of the increase of the glazing area on the heating demand is almost equal in all European climates, while in Riyadh is almost negligible. The differences within one climate when the glazing area is increased can be attributed to the increase of heat transfer through the glass which has worse insulation properties than the rest of the roof. Thus, it is possible to conclude that the losses through the glazing area in the winter months are greater than the solar gains, which are additionally reduced by the application of top coatings.

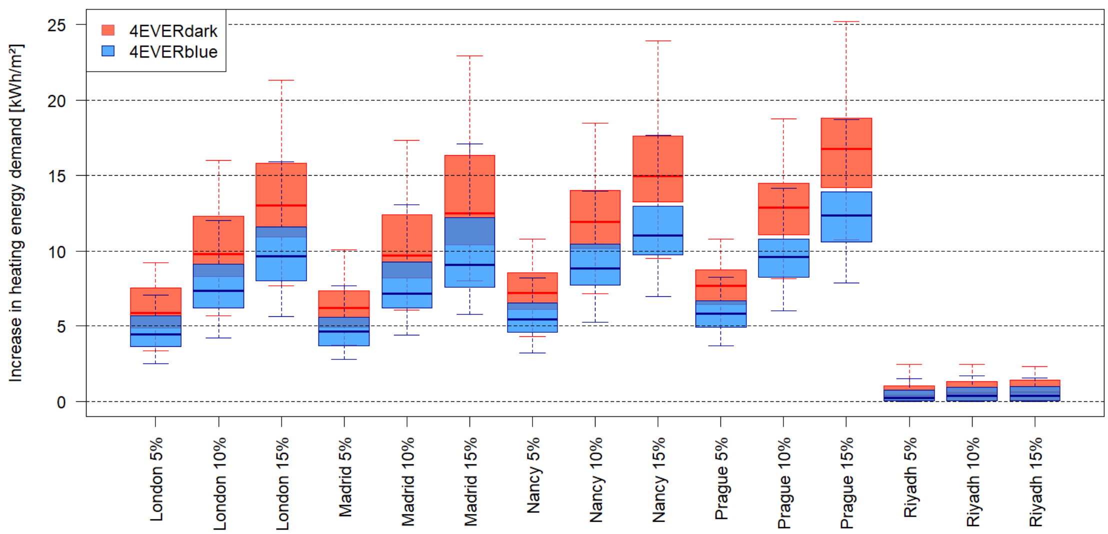


Figure 19 Increase in yearly heating demand shown as difference in kWh/m² for all models, conditions, climates and different glazing to roof ratios.

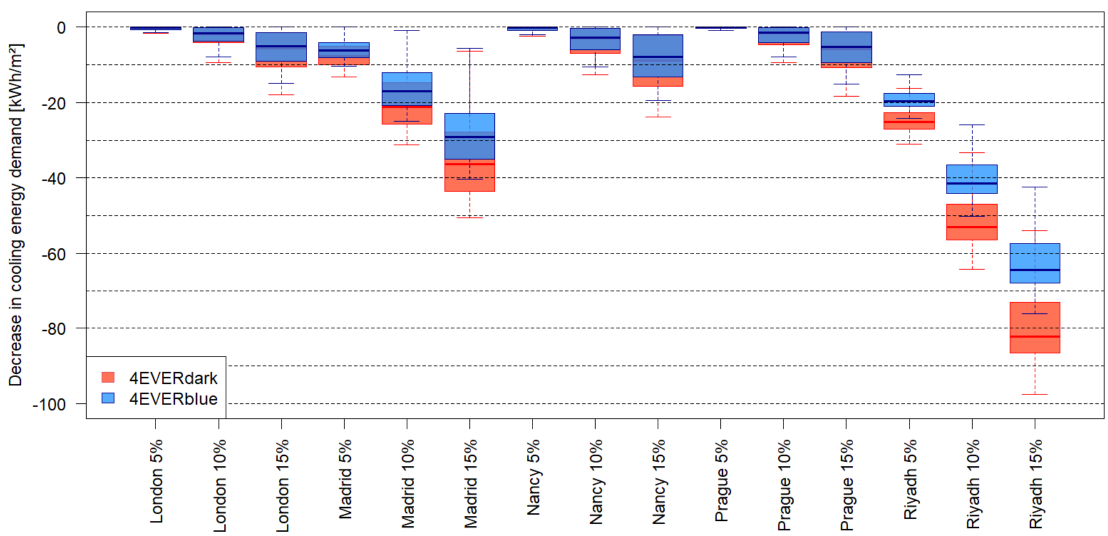


Figure 20 Decrease in yearly cooling demand shown as difference in kWh/m² for all models, conditions, climates and different glazing to roof ratios.

When observing the decrease in cooling demand, Figure 20, it is immediately noticeable how in warmer climates (Madrid, Riyadh) the application of top coatings has a very significant effect on energy savings. Moreover, the greater the glazing area the more pronounced is the impact. On the other hand in mild climates, although the impact does not seem large, it is important to notice that in some cases it is possible to increase the glazing area and keep the same energy demand after applying one of the top coatings. This can be beneficial in the aspect of providing more natural light in warehouses while having the same energy demand and indoor comfort.

In Figure 21, the difference in the yearly overheating hours is presented. Interestingly, in all climates, the decrease in the number of hours is within the same magnitude and surprisingly mild climates show the highest drops in overheating hours. However, it should be kept in mind that the baseline for warmer climates is higher than for mild climates, which means that in mild climates it is possible to reach even zero overheating hours, while in warm climates the total number is always higher.

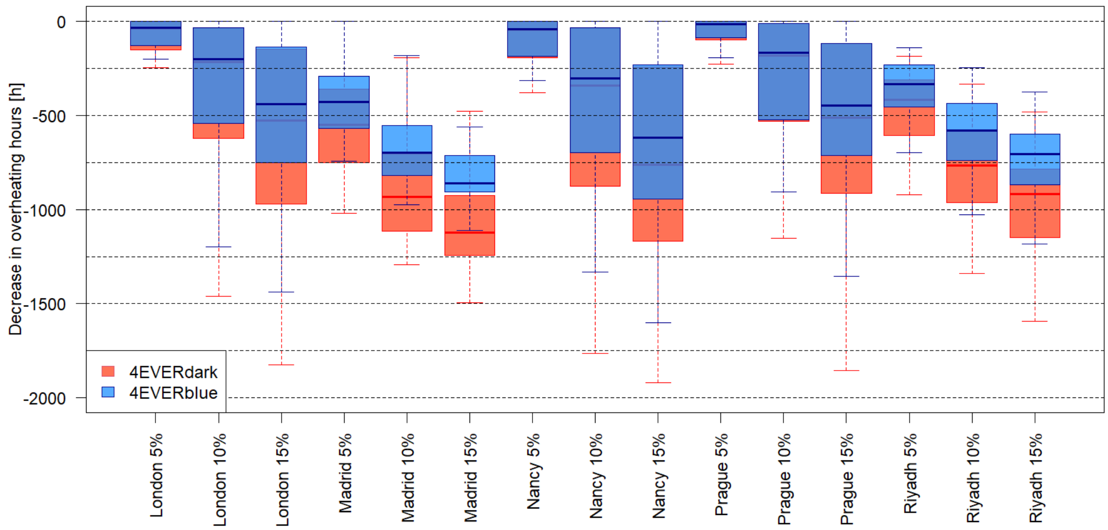


Figure 21 Decrease in overheating hours when applying top coatings shown as difference in the yearly number of hours for all models, conditions, climates and different glazing to roof ratios.

4.2. Impact of temperature regimes

This section explores the impact of different temperature regimes. While in the previous plots both temperature regimes were shown together, here the impact of the introduced assumptions is compared. As a reminder: temperature regime T1 represents a low comfort of the indoor climate, with the temperature boundaries at 16°C and 28°C, while regime T2 represents an increased comfort level where the boundaries are set at 19°C and 25°C. Consequently, when setting T2 is assumed the energy demand for both heating and cooling will be higher, and also the number of overheating hours.

Figure 22 shows the comparison of the heating demand when observing the two heating regimes in each climate. The relative difference between the two temperature settings produces a slight increase when a higher comfort is required, that is why the number of hours when heating is needed increases therefore also the impact of the coating is more visible.

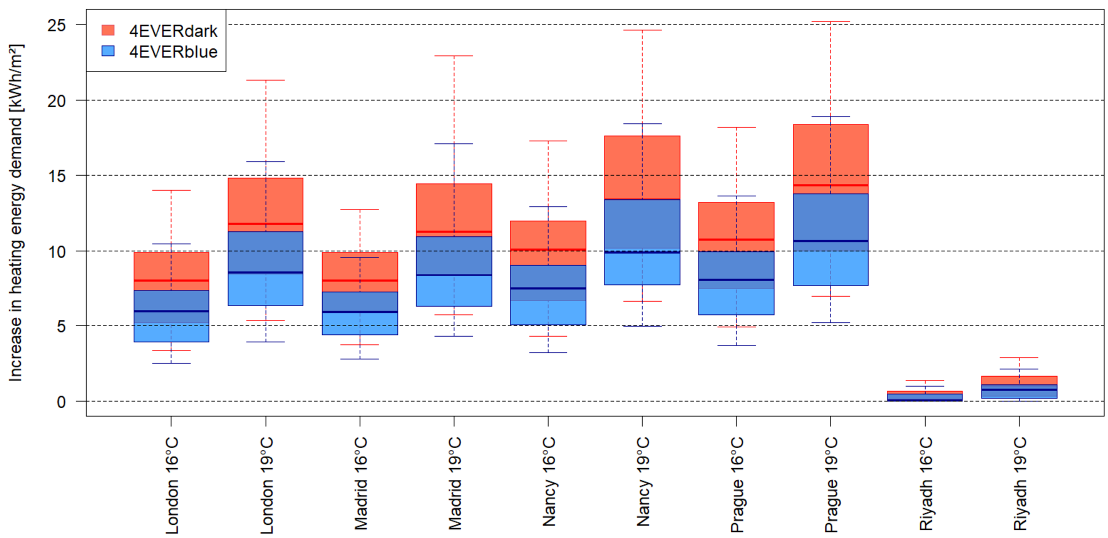


Figure 22 Increase in yearly heating demand shown as difference in kWh/m^2 for all models, conditions, climates and different temperature regimes.

The difference in the cooling demand when temperature regimes T1 and T2 are compared is presented in Figure 23. It is possible to notice a greater impact when applying top coatings on a warehouse with required higher comfort. That is because more energy is needed to maintain a temperature of 25°C than for 28°C, thus the effect of the savings because of the top coatings is more enhanced. Observing the five climates, despite the higher savings in warmer climates, the relative difference between T1 and T2 is equally pronounced.

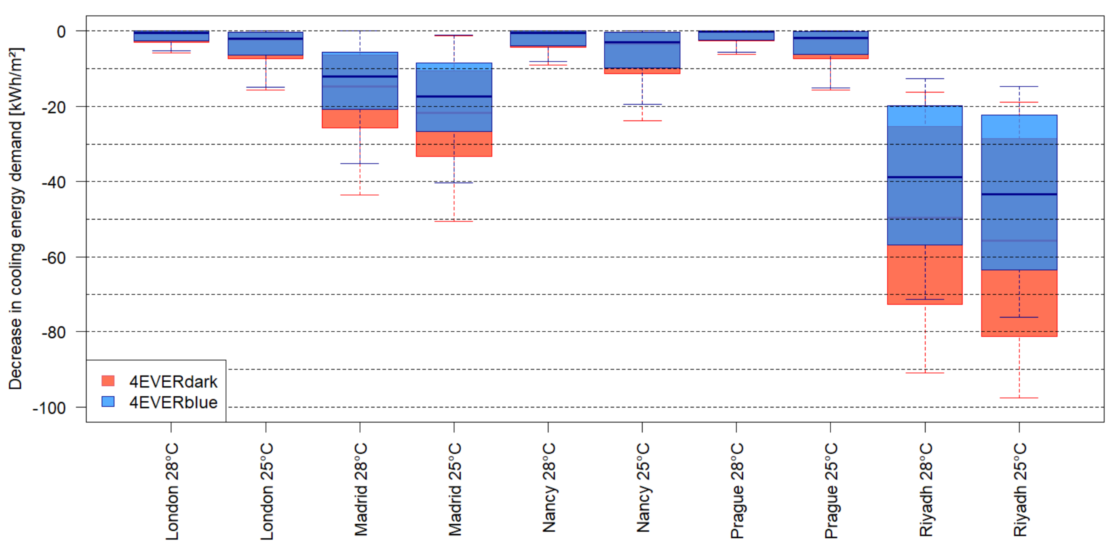


Figure 23 Decrease in yearly cooling demand shown as difference in kWh/m^2 for all models, conditions, climates and different temperature regimes.

Finally, in Figure 24, the decrease in overheating hours between the two temperature settings is compared. For mild climates (London, Nancy, Prague) the relation between T1 and T2 is similar and it indicates the simple fact that the warehouse's temperature is over 28°C less frequently than over 25°C, thus there is less space for improvement when applying top coatings. On the other hand, for Madrid and Riyadh, the indoor of the warehouse achieves a temperature of 25°C almost as frequently as 28°C thus the difference will be reflected more in the energy savings.

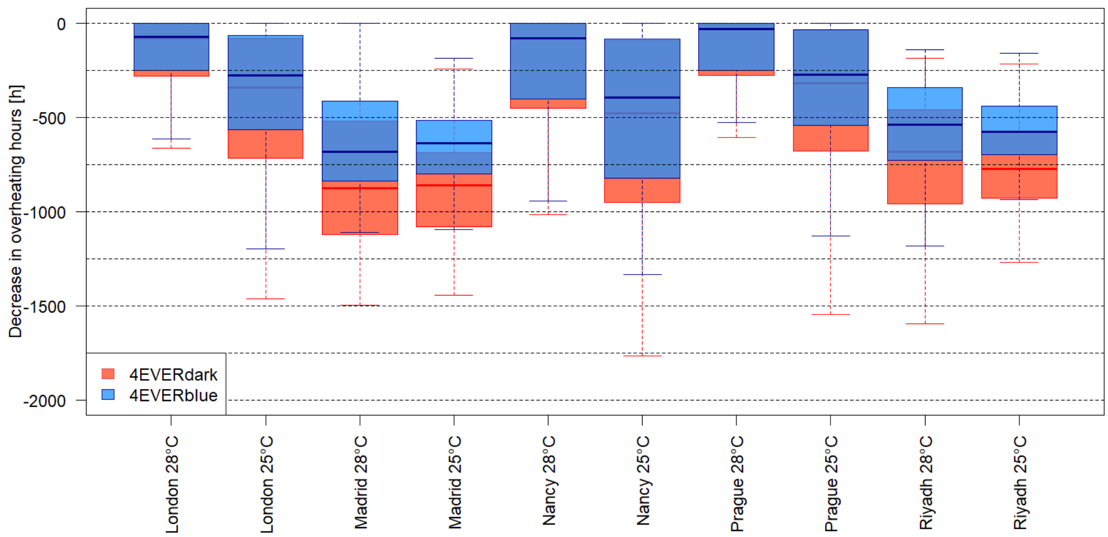
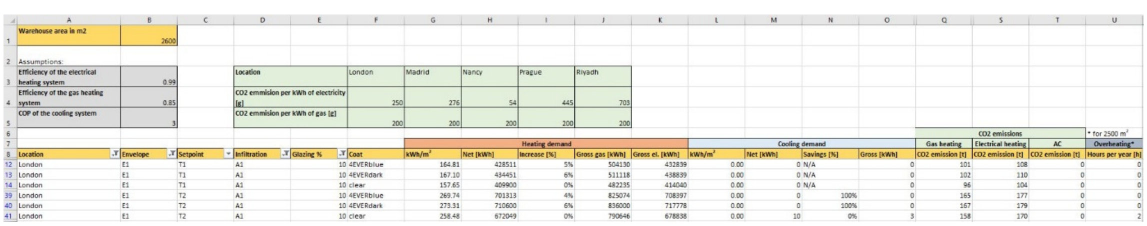


Figure 24 Decrease in overheating hours when applying top coatings shown as difference in the yearly number of hours for all models, conditions, climates and different temperature regimes.

5. Calculation tool

All the results presented in Chapter 4 are gathered and presented in form of an Excel calculation tool. Screenshots of the tool with the explanation of the content follow. In figure Figure 25, the layout is shown but since the tool has three main areas, each will be explained individually.



Warehouse area in m2	2600
Assumptions:	
Efficiency of the electrical heating system	0.99
Efficiency of the gas heating system	0.85
COP of the cooling system	3

Location	London	Madrid	Nancy	Prague	Riyadh
CO2 emmision per kWh of electricity [g]	250	276	54	445	703
CO2 emmision per kWh of gas [g]	200	200	200	200	200

						Heating demand					Cooling demand				CO2 emissions: Gas heating	CO2 emissions: Electrical heating	CO2 emissions: AC	Overheating* (* for 2500 m²)
Location	Envelope	Setpoint	Infiltration	Glazing %	Coat	kWh/m²	Net [kWh]	Increase [%]	Gross gas [kWh]	Gross el. [kWh]	kWh/m²	Net [kWh]	Savings [%]	Gross [kWh]	CO2 emission [t]	CO2 emission [t]	CO2 emission [t]	Hours per year [h]
London	E1	T1	A1	10	4EVERblue	164.81	428511	5%	504130	432839	0.00	0	N/A	0	101	108	0	0
London	E1	T1	A1	10	4EVERdark	167.10	434451	6%	511118	438839	0.00	0	N/A	0	102	110	0	0
London	E1	T1	A1	10	clear	157.65	409900	0%	482235	414040	0.00	0	N/A	0	96	104	0	0
London	E1	T2	A1	10	4EVERblue	269.74	701313	4%	825074	708397	0.00	0	100%	0	165	177	0	0
London	E1	T2	A1	10	4EVERdark	273.31	710600	6%	836000	717778	0.00	0	100%	0	167	179	0	0
London	E1	T2	A1	10	clear	258.48	672049	0%	790646	678838	0.00	10	0%	3	158	170	0	2

Figure 25 Print-screen of the Excel calculation tool

5.1. Excel calculation tool: inputs and assumptions

The first part of the calculation tool includes the cells in which inputs and assumed values can be inserted. Cell B1 contains the total area of the warehouse which is used to calculate the total energy demands for cooling and heating. Since in this study the warehouse's size was the same through all the simulations it was not possible to explore its impact, thus in the calculation tool, all results were transformed into values per m^2 by a simple division. It can be assumed that for smaller deviations from the original size (50 x 50 m) the results will still be valid. However, for larger deviations in size, the results in the calculation tool should be taken carefully. Some of the factors which may introduce errors are: the ratio of the envelope versus indoor volume, the ratio of the floor/roof area in comparison to the whole envelope and the significant increase in the glazing area when the total roof area is increased.

Cells marked in grey contain the assumed values related to the warehouse services. Here, two options of heating systems are assumed, first an electrical heating system with an efficiency of 99%, and a gas-fired system with an efficiency of 85%. Moreover, one option for the cooling system is given, and that is a system with the average COP = 3. All values can be changed if wanted, and the new value will be automatically selected by the cells where needed.

Cells marked in green are related to the CO_2 emissions. For each country, the CO_2 emissions in grams per kWh are chosen according to the average energy mix for the electricity production according to [7] and [8]. For the CO_2 emissions of gas, the same value is repeated in each country even though the composition of the gas might differ, these numbers can be arbitrarily adjusted.

	A	B	C	D	E	F	G	H	I	J
1	Warehouse area in m2	2500								
2	Assumptions:									
3	Energy conversion for electrical heating	0.99		Location		London	Madrid	Nancy	Prague	Riyadh
4	Energy conversion for gas heating	0.85		CO2 emmision per kWh of electricity [g]		250	276	54	445	703
5	COP of the cooling system	3		CO2 emmision per kWh of gas [g]		200	200	200	200	200

Figure 26 Print-screen of the Excel calculation tool: inputs and assumptions.

Cell	Explanation
B1	Total floor area of the warehouse [m2]
B3	Assumed efficiency of the electrical heating system
B4	Assumed efficiency of the gas heating system
B5	Assumed COP of the cooling system
F4 – J4	Assumed CO2 emissions per kWh of electricity [g]
F5 – J5	Assumed CO2 emissions per kWh of gas [g]

5.2. Excel calculation tool: filters

The second part of the calculation tool is a filter where the wanted combinations can be compared. It works as the already built-in Excel filter and it is possible to select the following parameters: location envelope, temperature setpoints, infiltration rates, glazing area and top coating. When in the filters all options are selected it shows all the performed simulations. More about the abbreviations found in the calculation tool can be found in Chapter 2.

	A	B	C	D	E	F
8	Location	Envelope	Setpoint	Infiltration	Glazing %	Coat
129	London	E3	T1	A2	10	4EVERblue
130	London	E3	T1	A2	10	4EVERdark
131	London	E3	T1	A2	10	clear
156	London	E3	T2	A2	10	4EVERblue
157	London	E3	T2	A2	10	4EVERdark
158	London	E3	T2	A2	10	clear

Figure 27 Print-screen of the Excel calculation tool: filtering section.

Cell	Explanation
A8	Location filter (options: London, Madrid, Nancy, Prague, Riyadh)
B8	Envelope filter (options: E1, E2, E3, E4, E5)
C8	Setpoint (temperature) regime filter (options: T1, T2)
D8	Infiltration (air exchange) rate filter (options: A1, A2, A3)
E8	Glazing to roof ratio [%] (options: 5, 10, 15)
F8	Coating type (options: Clear, 4EVERblue, 4EVERdark)

5.3. Excel calculation tool: results

The third part of the calculation tool shows the results computed using the inserted inputs and selected model variations. Columns G, L and U are fixed and input invariant, while other columns are being calculated. Column H shows the exact output from the simulation for the heating demand, thus the net energy, while columns J and K show the gross heating demand calculated according to the selected efficiencies. For cooling, column M shows the exact output from the simulation, thus the net energy, while column O shows the gross cooling demand calculated according to the selected COP. Columns P and R are hidden and their content is the following: P - CO_2 emissions per kWh of gas [g] (automatically selected according to the location) and R - CO_2 emissions per kWh of electricity [g] (automatically selected according to the location). Columns Q, S and T calculate the CO_2 emissions in tons per year according to the selected assumptions. Finally, column U shows the total number of overheating hours but calculated for the original size, thus not dependent on the size of the warehouse.

	G	H	I	J	K	L	M	N	O	Q	S	T	U
6											CO2 emissions		* for 2500 m^2
7			Heating demand					Cooling demand		Gas heating	Electrical	AC	Overheating*
8	kWh/m^2	Net [kWh]	Increase [%]	Gross gas [kWh]	Gross el. [kWh]	kWh/m^2	Net [kWh]	Savings [%]	Gross [kWh]	CO2 emission [t]	CO2 emission [t]	CO2 emission [t]	Hours per year [
12	164.81	428511	5%	504130	432839	0.00	0	N/A	0	101	108	0	0
13	167.10	434451	6%	511118	438839	0.00	0	N/A	0	102	110	0	0
14	157.65	409900	0%	482235	414040	0.00	0	N/A	0	96	104	0	0
39	269.74	701313	4%	825074	708397	0.00	0	100%	0	165	177	0	0
40	273.31	710600	6%	836000	717778	0.00	0	100%	0	167	179	0	0
41	258.48	672049	0%	790646	678838	0.00	10	0%	3	158	170	0	2

Figure 28 Print-screen of the Excel calculation tool: results section

Cell	Explanation
G8	Heating demand in kWh/m^2 per year for the selected simulations
H8	Net heating demand in kWh per year for the selected simulations and size
I8	Increase in the heating demand compared to the demand for the same model with clear glazing [%]
J8	Gross heating demand of the gas heating in kWh per year for the selected simulations and size
K8	Gross heating demand of the electrical heating in kWh per year for the selected simulations and size
L8	Cooling demand in kWh/m^2 per year for the selected simulations
M8	Net cooling demand in kWh per year for the selected simulations and size
N8	Decrease in the cooling demand compared to the demand for the same model with clear glazing [%]
O8	Gross cooling demand of the air conditioning in kWh per year for the selected simulations and size
Q8	CO_2 emissions if gas heating system is assumed [t]
S8	CO_2 emissions if electrical heating system is assumed [t]
T8	CO_2 emissions of the assumed air conditioning system [t]
U8	Overheating hours in one year (8760 h), calculated for a warehouse of 2500 m^2

6. Conclusion

Impact of the glazing to roof ratio

The heating demand increase is proportional to the increase in the glazed area (since the heat losses to the ambient increase) which is attributed to the augmented heat transfer through the glass (worse insulator than the rest of the roof). Moreover, the relative difference of the increase in the heating demand between top coatings is similar in all climates and it is caused by reduced solar gains when coatings are applied. Overall, the impact on the heating demand is almost equal in all European climates, while in Riyadh is almost negligible.

For the cooling demand, the impact of the glazing to roof ratio is more enhanced. Although the increase in demand is also proportional to the increase in glazing area, in this case, the difference is caused by greater solar gains through larger glazing. However, when top coatings are applied in mild climates the increase in glazing area does not produce an increase in cooling demand and overheating hours as significantly as in warm climates.

Impact of the temperature regime

Overall, a higher comfort represented by the T2 temperature settings requires a higher demand in both heating and cooling. Because this total energy requirement is higher, it is possible to notice a greater impact when applying top coatings.

Mild climates (London, Nancy, Prague)

For some cases, the application of the top coating on the glazed areas can fully replace the necessity of cooling systems and the total number of overheating hours can be significantly lowered and sometimes drawn to zero. In addition to that, the indoor climate keeps a better comfort level. In some cases, it is also possible to increase the glazing area and keep the same energy demand after applying one of the top coatings, which can be beneficial in the aspect of providing more natural light in warehouses while having the same energy demand and indoor comfort.

On the negative side, there might be a larger increase in heating demand than a decrease in cooling demand. However, the benefit of the installation can be justified because of presumably different costs or availability of the energy required for heating in comparison to cooling. For the cooling demand, because it is usually low, there is no significant difference in the performance of 4EVERblue and 4EVERdark.

Warm climates (Madrid, Riyadh)

Generally, the application of top coatings will have a greater impact on savings in the cooling season, than causing additional energy demand in the heating season. When observing the total yearly demand the application of top coatings can produce impressive savings. Additionally, it is noticed that the greater the glazing area (and hotter the climate) the more pronounced is the impact of the top coating. Moreover, if the cooling system is carefully designed, the required installed power can be lower.

However, since in warm climates the heating demand is low it is in some cases fully covered by solar gains, when solar gains are reduced by the application of top coatings it may lead to the necessity to install a heating system.

7. References

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