Energy, CO_2 and cost savings by using highly

energy-efficient plastic spacer bars

in comparison to aluminium and stainless steel spacer bars in different climates

Study by the Passivhaus Institut on behalf of SWISSPACER, Kreuzlingen, Switzerland

Report

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1 Introduction

Saving energy in order to reduce CO_2 emissions which are harmful to the climate and to relieve the burden on renewable energy sources is one of the most important tasks of our time. In the building-sector, energyefficiency has, besides energy savings many additional benefits They regularly go hand in hand with lower life cycle costs. This is particularly clear with spacer bars in low-e glazing: only a few cents more have to be invested for highly efficient spacer bars per meter glass-edge. In cool climates, up to 25 euros per metre can be saved in energy costs over the period of use compared with the usual aluminium spacer bars. Another significant benefit is that the temperatures at the edge of the glass are significantly increased with the highly efficient spacer bars. The area, in which use free from mildew and condensation is possible, is expanded considerably in this way.
This study was carried out by Dr. Wolfgang Feist, Passivhaus Institut. Dr. Wolfgang Feist. It discusses the potential savings by using highly energy-efficient plastic spacer bars in comparison to aluminium and stainless steel spacer bars using a building model in three different climates. A large number of manufacturers of warm edge spacer bars now offer energy-efficient products. The study uses SWISSPACER ULTIMATE spacer bars as an example.

2 Approach

2.1 Overview of the individual steps in the method

- Firstly, the thermal values of an aluminium, a stainless steel and a plastic spacer bar were calculated in combination with different reference frames and glazing.

- Using these values, the energy balance of a passive house building model was calculated in a second step with the Passive House Planning Package (PHPP, Version 9.4). Based on this, the savings in energy, energy costs and CO_2 in different climates were determined.

- In step 3, these results were applied to the linear metres at the edge of the glass and extrapolated to a high-rise building according to the passive house standard in step 4. The calculations were also repeated and reconciled using a simplified, alternative process as validation.

- Step 2 was repeated for the model of two low-energy houses (LEH), one with double, the other with triple glazing. The energy balance, as well as savings in energy, energy costs and CO_2 in three climates was also determined for these.

- Finally, the study investigates the effects of changing window surface area on the annual heating demands.

2.2 The spacer bar - frame combinations and their glass edge thermal bridge loss coefficients

As reference frames, this study uses the variants for cool, cool/moderate, warm/ moderate and warm climate from the 'wood-aluminium' range of the Passivhaus Institut's spacer bar certification (see Table 1).

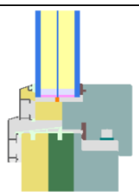
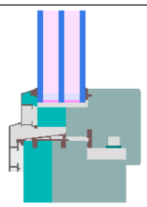
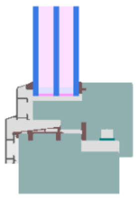
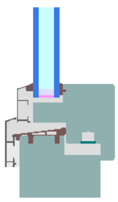
Frame	Value	Aluminium-spacer bar	Stainless steel spacer bar	Plastic spacer bar
	**Cool climate**. U_f = 0.57 W/(m²K), b_f = 12 cm Used for the Helsinki location			
	Ψ_g [W/(mK)]	0.119	0.054	0.028
	$f_{Rsi=0.25\ m^2K/W}$ [-]	0.48	0.67	0.76
	**Cool/moderate climate**. U_f = 0.75 W/(m²K), b_f = 12 cm Used for the Frankfurt location			
	Ψ_g [W/(mK)]	0.109	0.053	0.028
	$f_{Rsi=0.25\ m^2K/W}$ [-]	0.47	0.64	0.71
	**Warm/moderate / very hot climate**. U_f = 0,97 W/(m²K), b_f = 12 cm Used for the Bangalore location and for the LEH with triple glazing in all locations			
	Ψ_g [W/(mK)]	0.107	0.051	0.028
	$f_{Rsi=0.25\ m^2K/W}$ [-]	0.44	0.61	0.68
	**Warm climate**. U_f = 1.19 W/(m²K), b_f = 12 cm Used for the LEH with double glazing in all locations			
	Ψ_g [W/(mK)]	0.093	0.056	0.034
	$f_{Rsi=0.25\ m^2K/W}$ [-]	0.37	0.49	0.56

Table 1: Thermal values of the underlying spacer bar / frame combinations

All variants were calculated with polysulfide (0.40 W/(mK)) as secondary seal with a height of 3 mm (Box 1). The aluminium spacer bar was modelled with a height of 6.5 mm and a profile-width of 0.5 mm, 160 W/(mK), filled with silica gel as drying agent (0.13 W/(mK)). A thermal conductivity of Box 2 with 0.6 W/(mK) and a height of 7 mm was estimated for the stainless steel spacer bars. The thermal conductivity of Box 2 of the plastic spacer bar was assumed to be 0.14 W/(mK) with a height of 6.5 mm. All calculations were carried out with Flixo 7 pro (see appendix). The results are presented in Table 1. The hygiene criterion for windows in passive houses are only achieved with the plastic spacer bar for the variants in cool and cool/moderate climates, also with the stainless steel spacer bars in the warm/moderate climate.

2.3 The building model used and its locations

The locations chosen for the study are Frankfurt (Germany) for the cool/moderate, Helsinki (Finland) for the cool and Bangalore (India) for the very hot climate. Table 2 on the next page shows the heating- and cooling- degree hours of the locations.

The building model

The study works with a building model which was modelled with the Passive House Planning Package (PHPP). The model is based on the first passive house built in 1991 in Kranichstein. This solar-optimised row house with its large, glazed south-facing wall provides a calculation example to all PHPP users. The model is equipped with a heat pump which provides the heating and – supported by a thermal solar collector – the domestic hot water. A heat pump also provides the cooling system in the Bangalore location in India. So, the building is completely electrically powered. The passive house and both double and triple-glazed low-energy houses are variants of the same building model.

Figure 1:
The Kranichstein passive house is a solar-optimised row house with 156 m² living space on 2.5 floors

Features of individual building variants and locations

The maximum admissible annual heating demand for a passive house is 15 kWh/(m²a). For the passive house in Frankfurt, the annual heating demand was adjusted so that the 15 kWh/(m²a) was achieved with aluminium spacer bars. In this case, the use of stainless steel and plastic spacer bars leads to a lower annual heating demand. In the cool climate in Helsinki, this approach was not effective. The building would have needed uneconomically thick insulation. Therefore, the 15 kWh/(m²a) annual heating demand was adjusted with the plastic spacer bar. The heating requirement increases when using the stainless steel or aluminium spacer bar.

With respect to the hygiene criteria – namely restricting the risk of mould on the glass edge from too low temperatures – aluminium and stainless steel spacer bars are not recommended in the climatic conditions of Frankfurt and Helsinki.

For both low-energy house variants, the U-values for wall, roof and floor and the air extraction system (airtightness 1.5 1/h) of the reference building of the EnEV 2016 were assumed for all locations. For the variants with double glazing, the glass values of the EnEV 2016 (U_g 1.2 W/(m²K), g 0.6 see Appendix 1, Table 1 of the EnEV) were also applied. Exception: The g-value of 0.2 was chosen for the Bangalore climate.

As a model for the window frames for the double glazed low-energy house, the wood-aluminium frames in the 'warm' variant from the Passivhaus Institut's spacer bar certification were chosen. For the triple glazed low-energy house, the window frame model for the warm/moderate climate was used (see also Table 1). Here U_g is 0.7 W/(m²K), g 0.55.

Value	Unit	**Frankfurt**	**Helsinki**	**Bangalore**	**Double glazed LEH**	**Triple glazed LEH**
Heating degree hours	kKh/a	79	116	0		
Cooling degree hours	kKh/a	0	0	37		
Roof & exterior wall U-value	W/(m²K)	0.13	0.09	0.15	0.20 / 0.28	
Cellar roof U-value	W/(m²K)	0.30	0.14	0.30	0.35	
Window frames U-value	W/(m²K)	0.75	0.57	0.97	1.19	0.97
Glass U-value	W/(m²K)	0.70	0.52	0.52	1.20	0.70
Glass g-value	-	60%	50%	20%	60% / 20%	55% / 20%

Table 2: Climate values and building component qualities of the reference building

If there are people or warmth from appliances and lighting: in areas requiring heating, such internal heat sources help with the heating of a building. In contrast, in areas requiring cooling, such as India, they increase the cooling demand. They add to the cooling load in addition to the climatic loads, such as outside temperature, solar radiation and ventilation. Therefore, the cooling demand appears to be disproportionately high in comparison to the heating demand.

In order to reduce the solar load, the building in Bangalore was turned 180° so that the wall with the large windows only faced north. The walls and roofs were also painted with so-called ‘cool colours’. They absorb less radiation and have a positive impact on the cooling demand.

The inside temperature was adjusted to 20°C in all locations.
The specifications of the individual locations are summarised in Table 2.

2.4 How was the cash value of the energy savings determined?

In order to calculate the financial savings of the lower energy consumption, the study assumes the following boundary conditions: term of use: 40 years. Inflation-adjusted interest rate: 2%. Electricity price: Frankfurt 0.292 €/kWh, Helsinki 0.158 €/kWh (both from www.kwh-preise.de, accessed 20/10/2016), Bangalore 0.10 €/ kWh (according to the client).

Divided by the annual performance factors of the heat pumps, the price of heat in Frankfurt is 0.145 €/kWh and 0.089 €/kWh in Helsinki and the price of cooling in Bangalore is 0.05 €/kWh consistently over the period studied.

The cash values were determined with the following equations.

$$K_e = k_j \cdot B_B$$

$$k_j = Q_{Energie} \cdot k_{Energie}$$

$$B_B = \frac{1-(1+p_{real})^{t_B \cdot -1}}{p_{real}}$$

K_e: Cash value of the energy costs [€]
k_j: Annual energy costs [€]
B_B: Cash value factor for period studied [-]
$Q_{Energie}$: Amount of energy [kWh]
$k_{Energie}$: Energy costs [€/kWh]
p_{real}: Inflation-adjusted interest rate
t_B: Period studied [a]

2.5 How were the CO_2 savings calculated?

In order to determine the CO_2 savings, the energy demands for heating and cooling (energy source: electricity) were multiplied by the CO_2eq emissions factor. The CO_2eq emissions factor is also referred to as 'Global Warming Potential (GWP) Factor'. It contains not only the CO_2 produced per kWh of end energy, but also the climatic impact of other harmful gases standardised to the effect of CO_2.

The CO_2eq emissions factor in this study was estimated according to GEMIS 4.94, KW-Park Mix 2015 at 0.532 kgCO_2eq/ kWh_{End}. The value applies for Germany, which is in the process of an energy transition, and today already has a large proportion of renewable electricity. Therefore, the CO_2eq emissions factor is disproportionately low. The CO_2 savings are given per year, as the CO_2eq emissions factor of electricity is constantly falling during the energy transition. A summation over the period studied would therefore lead to false results.
As already mentioned, both the useful heat and the useful cooling output of the buildings studied is provided by heat pumps. According to PHPP, the annual COP for heating amounts to 2.01 (Frankfurt location) or 1.78 (Helsinki location), the annual COP for cooling is 2.0.

2.6 Converting the results into linear metres of the glass edge

In order to convert the results into linear metres of the glass edge, the savings for the whole Kranichstein building were divided by the linear metres of glass edge in the building. This is 99.1 metres.

2.7 Converting the results into the “passive house high-rise”

The values determined were converted into the “passive house high-rise” building model. To do this, the results per linear metre of glass edge in the Kranichstein passive house were multiplied by the linear metres of glass edge in the high-rise building. Per storey, this is 99.4 metres, a total of 1093.4 metres for 11 storeys. Figure 2 shows views and a floor plan of the high-rise building.

Figure 2: East and south view and floor plan of the ‘passive house high-rise’ building model

3 Results

Chapter 3 presents selected results from the study: the focus is on the figures concerning savings in energy, costs and CO_2 emissions from using highly energy-efficient plastic spacer bars in comparison to aluminium and stainless steel spacer bars in three different climates. The percentage energy savings always refer to the overall heating demand of the respective building. Here you will find key results and comments on the savings

- In the passive house (Chapter 3.1)
- In the passive house per linear metre of glass edge (Chapter 3.2)
- In the passive house high-rise building (Chapter 3.3)
- In the low-energy house with double low-e glazing (Chapter 3.5)
- In the low-energy house with triple low-e glazing (Chapter 3.6)
- Chapter 3.4. shows the validation of the results using the degree day
- Chapter 3.7. concludes with the question how the annual heating demand changes depending on the window sizes and the different spacer bars.

At the end of the study, there is an overview table with the results.

3.1 Results for the Kranichstein passive house building model

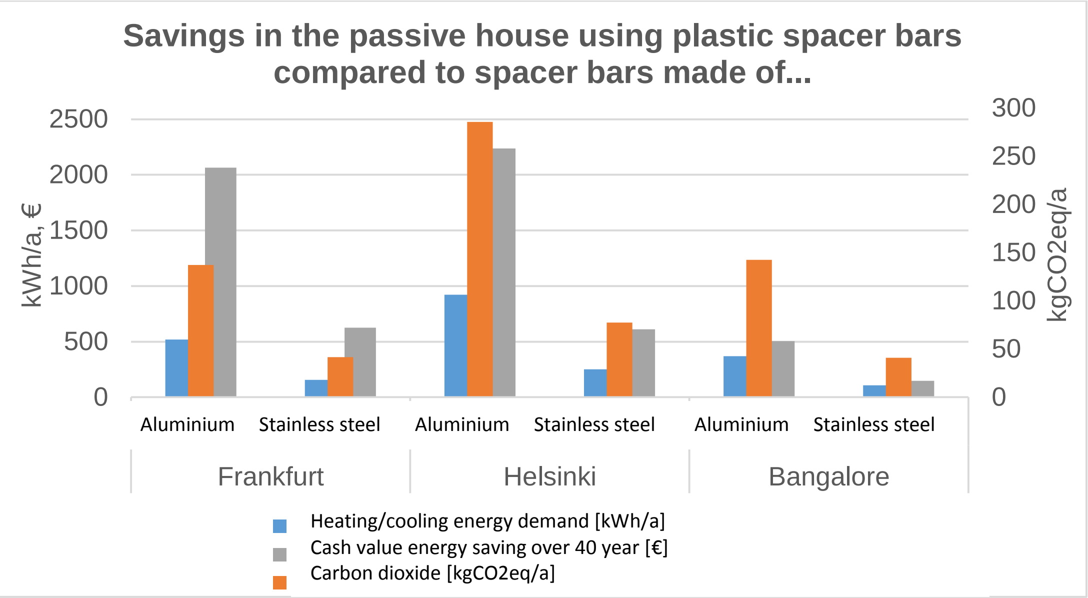


Figure 3: Energy, cost and CO_2 savings in the Kranichstein passive house building model

Results for the passive house in Frankfurt

The annual heating demand was calibrated to 15 kWh/(m²a) in the passive house in Frankfurt with the aluminium spacer bar. It is reduced

- by using the stainless steel spacer bar by 2.3 kWh/(m²a) to 12.7 kWh/(m²a)
- by using the plastic spacer bar again by 1.0 kWh/(m²a) to 11.7 kWh/(m²a)

Therefore, **the energy savings** amount to

- 22% with the plastic spacer bar instead of an aluminium spacer bar
- 8% with the plastic spacer bar instead of a stainless steel spacer bar

The carbon dioxide savings are as follows:
in comparison to the aluminium spacer bar

- 96 kg CO_2eq/a in 2015 with the stainless steel spacer bar
- 137 kg CO_2eq/a in 2015 with the plastic spacer bar
  That corresponds to driving approximately 1150 kilometres with a Golf VI 1.6 TDI

in comparison to the stainless steel spacer bar

- 42 kg CO_2eq/a in 2015 with the plastic spacer bar

The financial savings due to the lower heating demand over the assumed use cycle of the spacer bars of 40 years amount to:
in comparison to the aluminium spacer bar

- approx. €1,440 with the stainless steel spacer bar
- approx. €2,060 with the plastic spacer bar

in comparison to the stainless steel spacer bar

- approx. €620 with the plastic spacer bar

Results for the passive house in Helsinki

It is obviously cooler in Helsinki, Finland, than Frankfurt. That can be seen in degree days: it amounts to 79 kKh/a in Frankfurt and 119 kKh/a in Helsinki. Also higher are the potential savings from using highly energy-efficient components, such as plastic spacer bars.
The annual heating demand for the passive house in Helsinki with the plastic spacer bar was calibrated to 15 kWh/(m²a). In order to achieve this value in the cool Finnish climate with the aluminium spacer bar, disproportionately thick insulation would have been required – specifically wall insulation with a thickness of 105 cm, 71 cm more than with the plastic spacer bar. If both the wall and roof were improved, the insulation would need to be increased by 35 cm.

The annual heating demand is increased in comparison to the plastic spacer bar

- to 16.7 kWh/(m²a) with the stainless steel spacer bar
- to 21 kWh/(m²a) with the aluminium spacer bar

The energy savings therefore amount to

- 28 % with the plastic spacer bar instead of the aluminium spacer bar
- 10 % with the plastic spacer bar instead of the stainless steel spacer bar

The carbon dioxide savings are as follows:
in comparison to the aluminium spacer bar

- 208 kg CO_2eq/a in 2015 with the stainless spacer bar
- 286 kg CO_2eq/a in 2015 with the plastic spacer bar.
  That corresponds to driving approximately 2400 kilometres with a Golf VI 1.6 TDI.

in comparison to the stainless steel spacer bar

- 78 kg CO_2eq/a in 2015 with the plastic spacer bar

The financial savings through the lower heating demand over the spacer bars' assumed use cycle of 40 years amount to:
in comparison to the aluminium spacer bar

- approx. €1,620 with the stainless steel spacer bar
- approx. €2,240 with the plastic spacer bar

in comparison to the stainless steel spacer bar

- approx. €610 with the plastic spacer bar

Results for the passive house in Bangalore

In Bangalore, India, there is no heating demand due to the hot climate. However, there is a high cooling and dehumidifying demand. The dehumidifying demand is not considered here as it is separate from the thermal qualities of the building structure.

The annual cooling demand is

- 56.4 kWh/(m²a) with the plastic spacer bar
- 57.1 kWh/(m²a) with the stainless steel spacer bar
- 58.8 kWh/(m²a) with the aluminium spacer bar

The energy savings are lower in comparison to the heating climates. They are

- 4.0% with the plastic spacer bar instead of the aluminium spacer bar
- 1.2% with the plastic spacer bar instead of the stainless steel spacer bar

The carbon dioxide savings are as follows:
in comparison to the aluminium spacer bar

- 102 kg CO_2eq/a in 2015 with the stainless steel spacer bar
- 143 kg CO_2eq/a in 2015 with the plastic spacer bar
  That corresponds to approximately driving 1200 kilometres with a Golf VI 1.6 TDI.

in comparison to the stainless steel spacer bar

- 41 kg CO_2eq/a in 2015 with the plastic spacer bar

The financial savings through the lower cooling energy demand over the spacer bars' assumed use cycle of 40 years, with an assumed electricity price of 0.1 €/kWh, amount to:
in comparison to the aluminium spacer bar

- approx. €360 with the stainless steel spacer bar
- approx. €500 with the plastic spacer bar

in comparison to the stainless steel spacer bar

- approx. €150 with the plastic spacer bar

3.2 Results per linear metre of glass edge in the passive house

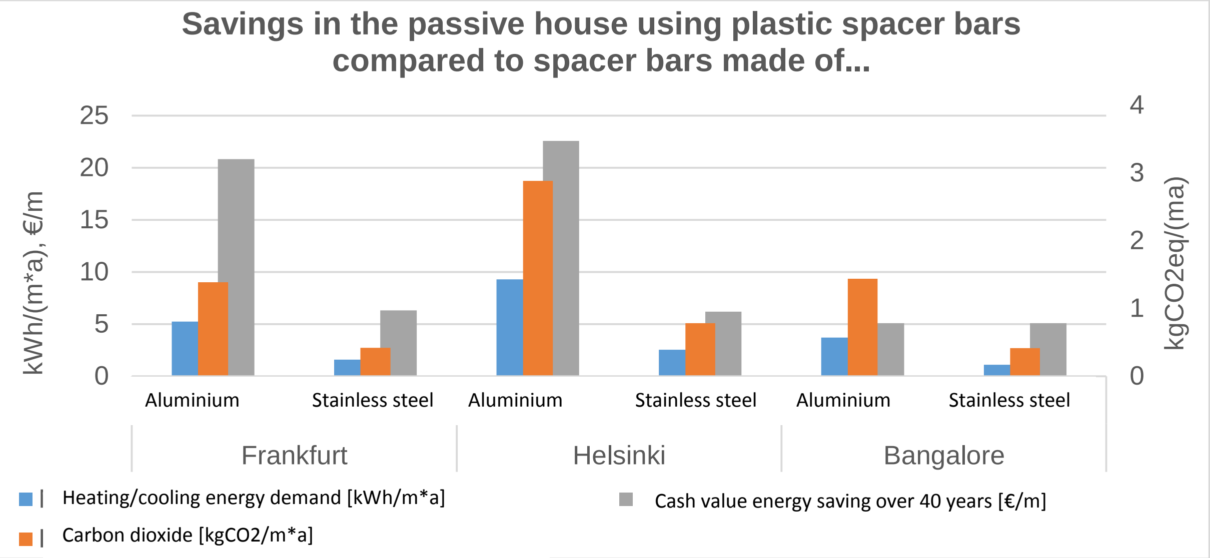


Figure 4: Savings in the passive house building model per linear metre of glass edge

Results per linear metre of glass edge in the passive house in Frankfurt

The savings per linear metre in comparison to the aluminium spacer bar are as follows:
for the stainless steel spacer bar

- 3.66 kWh/(m*a) thermal heat demand
- 0.97 kg CO_2eq/(m*a) carbon dioxide
- 15 €/m energy costs over 40 years of use

for the plastic spacer bar

- 5.25 kWh/(m*a) thermal heat demand
- 1.4 kg CO_2eq/(m*a) carbon dioxide
- 21 €/m energy costs over 40 years of use

The savings per linear metre in comparison to the stainless steel spacer bar are as follows:
with the plastic spacer bar

- 1.59 kWh/(m*a) thermal heat demand
- 0.42 kg CO_2eq/(m*a) carbon dioxide
- 6 €/m energy costs over 40 years of use

Results per linear metre of glass edge in the passive house in Helsinki

The savings are higher in cooler Helsinki.

The savings per linear metre in comparison to the aluminium spacer bar are as follows:
with the stainless steel spacer bar

- 6.75 kWh/(m*a) thermal heat demand
- 2.10 kg CO_2eq/(m*a) carbon dioxide
- 16 €/m energy costs over 40 years of use

with the plastic spacer bar

- 9.3 kWh/(m*a) thermal heat demand
- 2.88 kg CO_2eq/(m*a) carbon dioxide
- 23 €/m energy costs over 40 years of use

The savings per linear metre in comparison to the stainless steel spacer bar are as follows:
with the plastic spacer bar

- 2.55 kWh/(m*a) energy for heating
- 0.78 CO_2eq/(m*a) carbon dioxide
- 6 €/m energy costs over 40 years of use

Results per linear metre of glass edge in the passive house in Bangalore

The savings are lower in the areas requiring cooling in Bangalore.

The savings per linear metre in comparison to the aluminium spacer bar are as follows:
with the stainless steel spacer bar

- 2.63 kWh/(m*a) useful cooling energy
- 1.03 kg CO_2eq/(m*a) carbon dioxide
- 4 €/m energy costs over 40 years of use

with the plastic spacer bar

- 3.72 kWh/(m*a) useful cooling energy
- 1.44 kg CO_2eq/(m*a) carbon dioxide
- 5 €/m energy costs over 40 years of use

The savings per linear metre in comparison to the stainless steel spacer bar are as

follows:

with the plastic spacer bar

- 1.1 kWh/(m*a) useful cooling energy
- 0.41 CO_2eq/(m*a) carbon dioxide
- 1.5 €/m energy costs over 40 years of use

3.3 Results for the high-rise building model

In order to determine the values for the multi-storey residential building, the study researches the influence of the spacer bars on the heating energy demand of a high-rise building with the passive house standard. To do this, the results per metre of glass edge in the passive house (Chapter 3.2) were multiplied with the glass edge lengths of the high-rise building. This is 99.4 metres per storey and 1.93.4 metres for 11 storeys.
Figure 5 shows selected results.

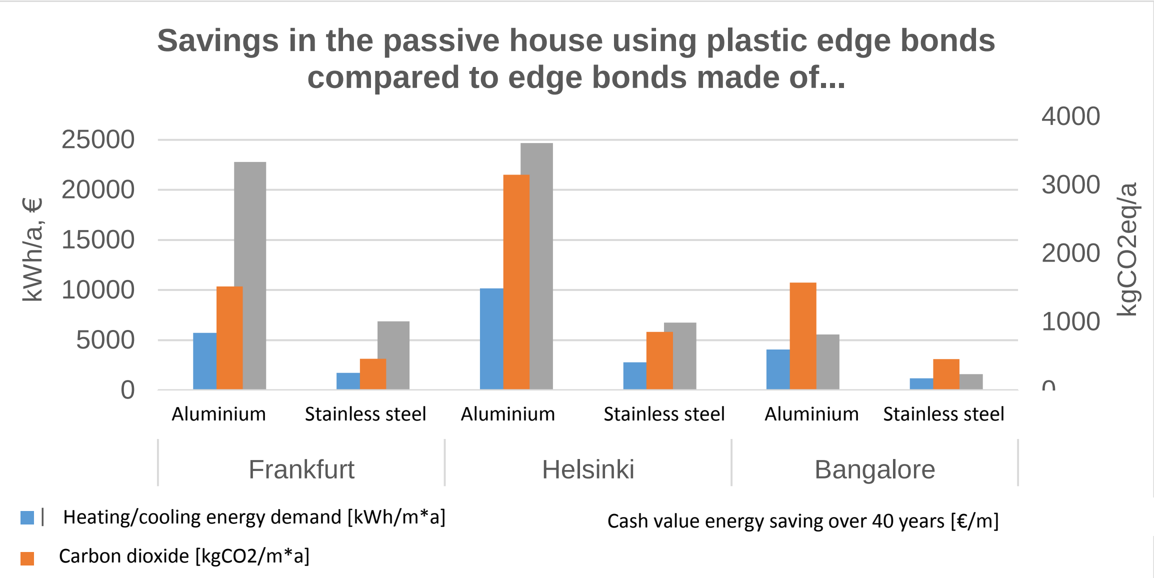


Figure 5: Visualising selected results for the building type ‚high-rise building with the passive house standard'

Results for the high-rise building with the passive house standard in Frankfurt

The savings in comparison to the aluminium spacer bar are as follows:
with the stainless steel spacer bar

- 4 MWh/a thermal heat demand
- approx. 1.1 tonnes CO_2eq/a carbon dioxide equivalent
- approx. €16,000 energy costs over 40 years of use

with the plastic spacer bar

- 5.7 MWh/a thermal heat demand
- approx. 1.5 tonnes CO_2eq/a carbon dioxide equivalent
- approx. €23,000 energy costs over 40 years of use

The savings in comparison to the stainless steel spacer bar are as follows:
with the plastic spacer bar

- 1.6 MWh/a thermal heat demand
- 495 kg CO_2eq/a carbon dioxide equivalent
- approx. €7,000 energy costs over 40 years of use

Results for the high-rise building with the passive house standard in Helsinki

The savings are higher in cooler Helsinki

The savings in comparison to the aluminium spacer bar are as follows:
for the stainless steel spacer bar

- 7 MWh/a thermal heat demand
- 2.3 tonnes CO_2eq/a carbon dioxide equivalent
- €18,000 energy costs over 40 years of use

for the plastic spacer bar

- 10 MWh/a thermal heat demand
- ca.3.2 tonnes CO_2eq/a carbon dioxide equivalent
- approx. €25,000 energy costs over 40 years of use

The savings in comparison to the stainless steel spacer bar are as follows:
with the plastic spacer bar

- 2.8 MWh/a thermal heat demand
- approx. 0.9 tonnes CO_2eq/a carbon dioxide equivalent
- approx. €7,000 energy costs over 40 years of use

Results for the high-rise building with the passive house standard in Bangalore

The savings are lower in the areas requiring cooling in Bangalore.

The savings in comparison to the aluminium spacer bar are as follows:
with the stainless steel spacer bar

- 2.9 MWh/a useful cooling energy
- 1.1 tonnes CO_2eq/a carbon dioxide equivalent
- €3,900 energy costs over 40 years of use

with the plastic spacer bar

- 4.1 MWh/a useful cooling energy
- approx. 1.6 tonnes CO_2eq/a carbon dioxide equivalent
- approx. €5,600 energy costs over 40 years of use

The savings in comparison to the stainless steel spacer bar are as follows:
with the plastic spacer bar

- 1.2 MWh/a useful cooling energy
- approx. 0.45 tonnes CO_2eq/a carbon dioxide equivalent
- approx. €1,600 energy costs over 40 years of use

3.4 Control calculation using degree days

As a control calculation, the savings per metre of glass edge were determined for all locations using degree days for the plastic spacer bar, compared with the aluminium spacer bar.

For this, the difference from the glass edge thermal bridge losses of the spacer bars were calculated and the result multiplied by the sum of heating- and cooling degree days. This approach is less precise than the approach chosen in this study and serve here to validate the results. The less precise approach overestimates the savings by 18% at the Frankfurt location, by 12% at the Helsinki location. At the Bangalore location, the savings are underestimated by 27%.

3.5 Results for the low-energy house with double glazing

In comparison to the passive houses, the low-energy houses examined in the study have a building envelope with worse thermal properties, ventilation without heat recovery and are less airtight: hence, the low-energy house variants have a significantly higher cooling or heating demands than the passive house variants. At the same time, the higher energy demand means that the relative savings from using better spacer bars are lower for a low-energy house.

Moreover, the differences in the glass edge thermal bridge coefficients of the different spacer bars of the frame-glass combination chosen here are lower than for the passive houses (see Table 1). Therefore, the savings to be made here are also lower (see Figure 6 and 7). However, in the double glazed low-energy house at the Frankfurt location, 5.6% of the heating energy demand for the whole building is saved if plastic spacer bars are used instead of aluminium spacer bars.

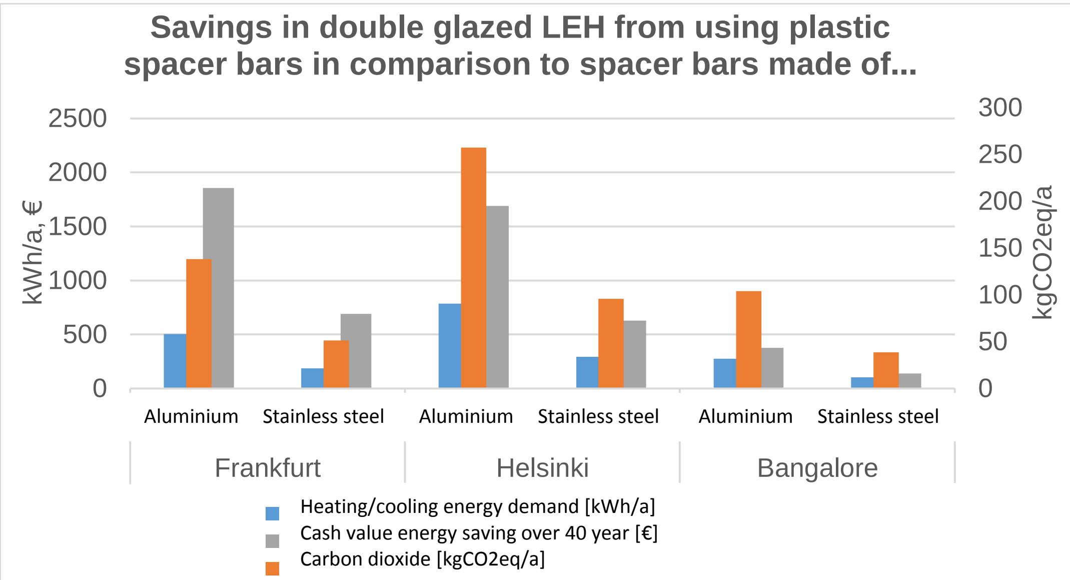


Figure 6: Savings in the double glazed low-energy house building model in Kranichstein

The annual heating demand (in Frankfurt and Helsinki)
or annual cooling demand (in Bangalore) is as follows:
with the plastic spacer bar in the double glazed low-energy house

- approx. 54 kWh/(m²a) in Frankfurt
- approx. 100 kWh/(m²a) in Helsinki.
- approx. 87 kWh/(m²a) in Bangalore

The savings in comparison to the aluminium spacer bar are as follows:
with the plastic spacer bar in Frankfurt

- 5.6 % of the whole building's heating energy demand
- 138 kg CO_2eq/a carbon dioxide
  That corresponds to driving approximately 1160 kilometres with a Golf VI 1.6 TDI.
- €1854 energy costs over 40 years of use
- approx. €19 per metre of glass edge

with the plastic spacer bar in Helsinki

- 4.8 % of the whole building's heating energy demand
- 257 kg CO_2eq/a carbon dioxide
  That corresponds to driving approximately 2160 kilometres with a Golf VI 1.6 TDI.
- €1690 energy costs over 40 years of use
- approx. €17 per metre of glass edge (due to the significantly lower electricity price)

with the plastic spacer bar in Bangalore

- 1.9 % of the whole building's cooling energy demand
- 104 kg CO_2eq/a carbon dioxide
  That corresponds to driving approximately 874 kilometres with a Golf VI 1.6 TDI.
- €376 energy costs over 40 years of use
- approx. €4 per metre of glass edge

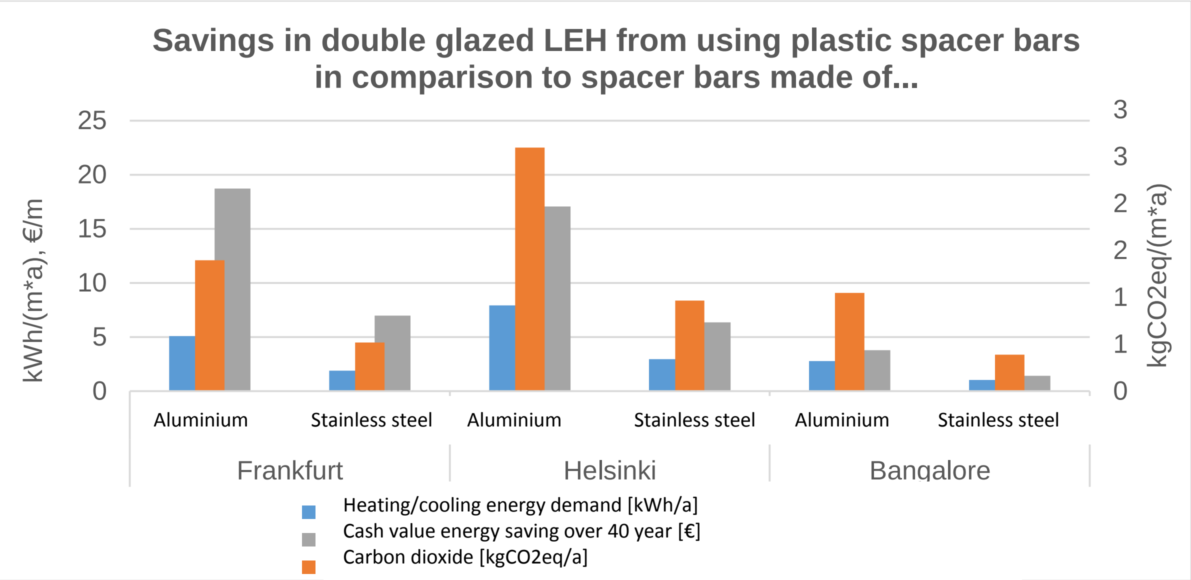


Figure 7: Savings per linear metre of glass edge in the double glazed low-energy house building model

3.6 Results for the low-energy house with triple glazing

In comparison to the double glazed low-energy house, the heating or cooling demand is reduced here by using slightly improved triple glazed frames and triple glazing.
In the triple glazed low-energy house at the Frankfurt location, 8.6% of the whole building's heating energy demand is saved if plastic spacer bars are used instead of aluminium spacer bars.

The annual heating demand (in Frankfurt and Helsinki)
or annual cooling demand (in Bangalore) is as follows:
with the plastic spacer bars in the triple glazed low-energy house

- approx. 46 kWh/(m²a) in Frankfurt
- approx. 88 kWh/(m²a) in Helsinki
- approx. 82 kWh/(m²a) in Bangalore

The savings in comparison to the aluminium spacer bar are as follows:
with the plastic spacer bar in Frankfurt

- 8.6 % of the whole building's heating energy demand
- 183 kg CO_2eq/a carbon dioxide
  That corresponds to driving 1538 kilometres with a Golf VI 1.6 TDI.
- €2463 energy costs over 40 years of use
- approx. €25 per metre of glass edge

with the plastic spacer bar in Helsinki

- 7.1 % of the whole building's heating energy demand
- 343 kg CO_2eq/a carbon dioxide
  That corresponds to driving 2882 kilometres with a Golf VI 1.6 TDI.
- €2255 energy costs over 40 years
- approx. €23 per metre of glass edge
  (higher energy savings than in Frankfurt, but lower electricity price)

with the plastic spacer bar in Bangalore

- 2.8 % of the whole building's cooling energy demand
- 143 kg CO_2eq/a carbon dioxide
  That corresponds to driving 1202 kilometres with a Golf VI 1.6 TDI.
- €504 energy costs over 40 years of use
- approx. €5 per metre of glass edge

Figure 8 and Figure 9 are a visual representation of the results for the low-energy house with triple glazing.

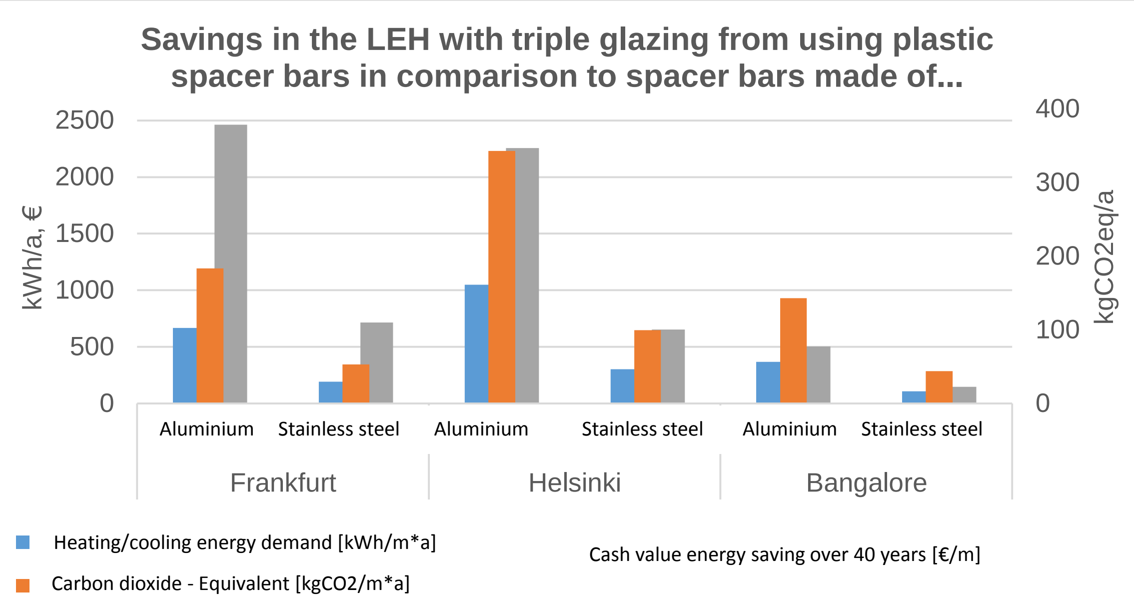


Figure 8: Savings in the triple glazed low-energy house building model

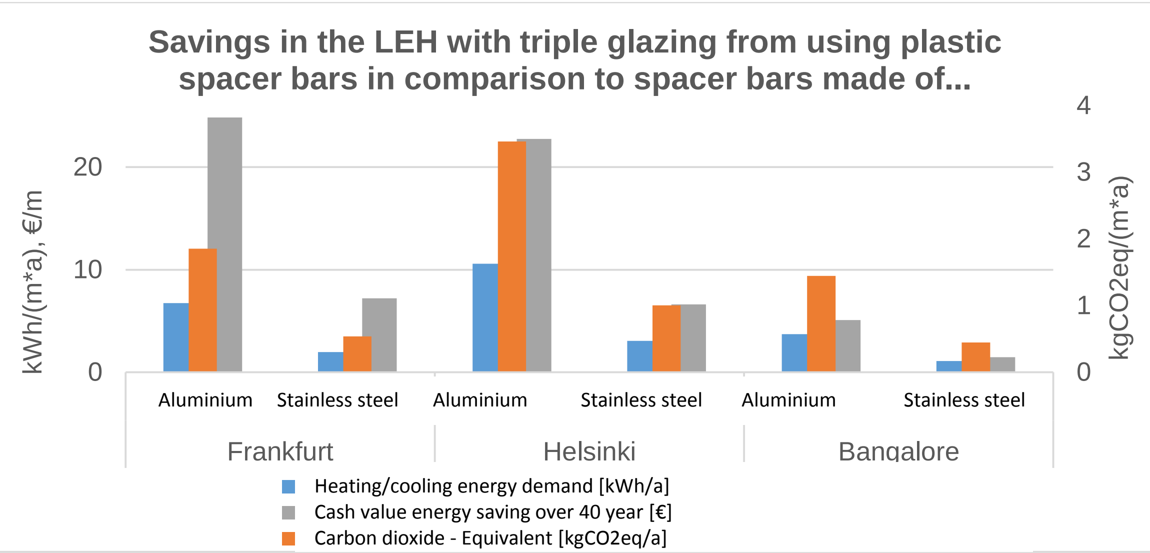


Figure 9: Savings per linear metre of glass edge in the triple glazed low-energy house building model

3.7 How does the annual heating demand change depending on the size of the windows and the spacer bars?

Varying the south-facing windows

The question of how the annual heating demand changes with the size of the window surface areas and the different spacer bars is also interesting. In order to study this, the number of south-facing windows in the 'Frankfurt passive house' building model were varied as an example. Originally, the passive house had 4 windows per storey. Now the number of south-facing windows is changed from 3 up to 18, from 1 up to 6 per storey.
The results are presented in **Figure 10**.

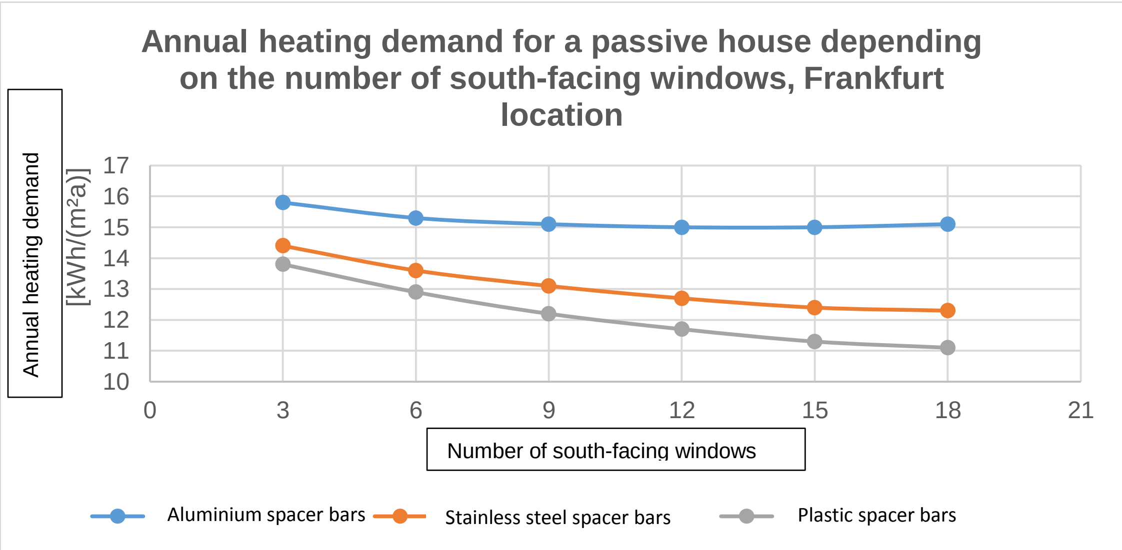


Figure 10: Change to the annual heating demand depending on the number of south-facing windows.

The annual heating demand initially falls in all variants with increasing window size: the additional heat gains exceed the additional heat losses. This effect is only reversed with the aluminium spacer bar – through proportionally increasing heat losses but relatively reducing usable heat gains – for a large number of windows.

Varying west or east-facing windows

The variation was repeated for the windows on the west side of the row house. Here there was initially only one window on the ground floor. As more transmission heat losses are expected than solar gains on the west side, glass with an optimised U-value of 0.52 W/(m²K) and a g-value of 50% was chosen for the window. The results are presented in Figure 11.

It shows that with all spacer bar variants, the heating demand increases with the number of windows: The losses are always higher than any solar gains to be made. However, the increase is lower with the better spacer bars than with the aluminium spacer bar.

The results can be approximately transferred to an east-facing facade.

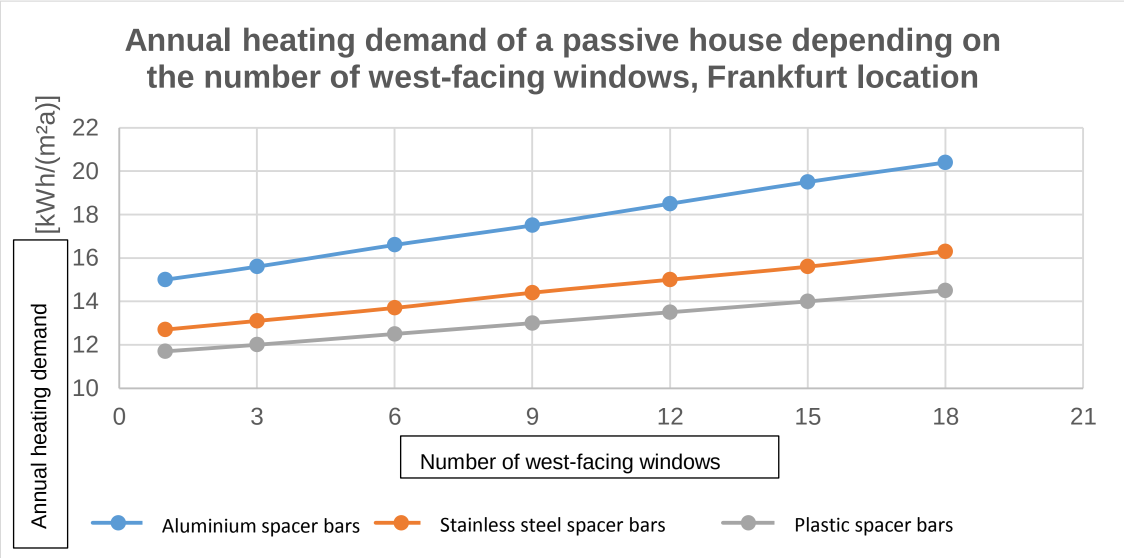


Figure 11: Change to the annual heating demand depending on the number of west-facing windows

Varying south and west-facing windows

Finally, the effect of a combination of the windows on the south and west sides on the annual heating demand was studied: a 3:1 ratio of south to west-facing windows was chosen. The results are presented in Figure 12.

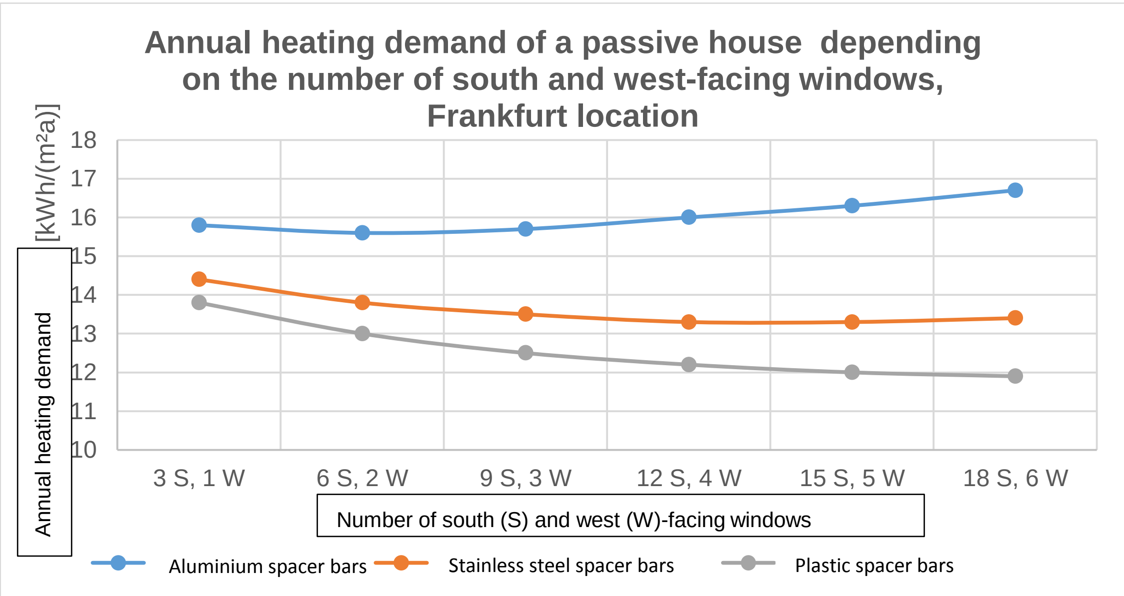


Figure 12: Change to the annual heating demand depending on the number of south and west-facing windows

The optimum heating demand is

- 6 south and 2 west-facing windows with aluminium spacer bars
- 12 south and 4 west-facing windows with stainless steel spacer bars
- The maximum number of windows studied of 18 south and 6 west-facing windows with plastic spacer bars due to the lowest heat losses

4 Summary

This study performed by the Passivhaus Institut shows that using highly energy-efficient plastic spacer bars in windows with insulated glass has many benefits. The energy – and therefore the CO_2 – and cost savings are considerable. Moreover, the hygiene situation at the edge of the glass is significantly improved, meaning that the risk of condensation or mould at the edge of the glass is significantly reduced. This applies in particular in comparison to aluminium, but also compared with stainless steel spacer bars. The cooler or hotter a climate is – or, more specifically: the more the outside climate differs from the desired inside climate – the higher the potential energy and CO_2 savings.

The cost benefits are, apart from the energy savings, strongly dependent on the respective energy prices. For example, that is why the energy cost savings over the service life in the passive house in Frankfurt and Helsinki are approximately the same, at approx. €21 or €23 per linear metre of spacer bar – despite a significantly higher energy saving and due to the low electricity price in Helsinki. Despite the relatively low electricity costs in Bangalore, India, €5 is saved –with the plastic spacer bar instead of the aluminium spacer bar in each case. It must be noted here that the average monthly income in India is 25 times lower (Germany approx. €3,100, India approx. €125, see www.laenderdaten.info, accessed 20/10/2015), electricity costs are therefore approximately 4 times higher relative to income.

In the cool climate, passive houses without highly energy-efficient spacer bars are usually not feasible – and that is in respect to both hygiene and efficiency.

Highly efficient spacer bars create additional room for manoeuvre in building design. The variation of the number of windows shows that. The east and west-facing sides of buildings can have bigger windows due to lower energy losses with highly efficient plastic spacer bars. On the south side, they reduce heating energy demands – even until the facade is entirely glazed.

With a view to protecting the climate, energy saving measures are also significant to the topic of “highly energy-efficient spacer bars”. For example, the CO_2eq emissions of 286 kg CO_2eq prevented in the passive house in Helsinki with the plastic spacer bar in comparison to the aluminium spacer bar in 2015 corresponds to driving approx. 2400 km in a Golf VI 1.6 TDI per year.

The savings determined for the passive house can be transferred to buildings with lower energy standards if the same glass / frame combinations are chosen. If, as in the low-energy house variants researched here, less thermally optimum frames and glazing are used, the potential savings fall, however the basic message is the same: irrespective of the glass, frame, building or climate, the use of highly energy-efficient spacer bars is strongly recommended.

5 Tables

(SWS U = the highly efficient plastic “Swisspacer Ultimate” spacer bar)

Results for the passive house

Location	Annual heating demand		
	[kWh/m²a]		
	Swisspacer Ultimate	Stainless steel spacer bar	Aluminium spacer bar
Frankfurt	11.7	12.7	15
Helsinki	15	16.7	21
	Annual cooling demand		
	[kWh/m²a]		
	Swisspacer Ultimate	Stainless steel spacer bar	Aluminium spacer bar
Bangalore	56.4	57.1	58.8

Location	Savings			
	Heat energy			
	[%]		kWh/(m*a)	
	SWS U vs stainless steel	SWS U vs Alu	SWS U vs stainless steel	SWS U vs Alu
Frankfurt	8	22	1.59	5.25
Helsinki	10	28	2.55	9.3
	Cooling energy			
	[%]		kWh/(m*a)	
	SWS U vs stainless steel	SWS U vs Alu	SWS U vs stainless steel	SWS U vs Alu
Bangalore	1.2	4	1.1	3.72

Location	Savings					
	CO_2					
	[kg CO_2 eq/a]		[(km Go F VI 1.6 TDI)/a]		[kg CO2eq/(m*a)] (assumed from the passive house)	
	SWS U vs stainless steel	SWS U vs Alu	SWS U vs stainless steel	SWS U vs Alu	SWS U vs stainless steel	SWS U vs Alu
Frankfurt	42	137	349	1150	0.42	1.4
Helsinki	78	286	650	2400	0.78	2.88
Bangalore	41	143	345	1200	0.41	1.44

Location	Savings			
	Monetary			
	[€/40a]		[€/ (linear metre of glass edge x 40a)] (assumed from the passive house model)	
	SWS U vs stainless steel	SWS U vs Alu	SWS U vs stainless steel	SWS U vs Alu
Frankfurt	624	2060	6	21
Helsinki	612	2240	6	23
Bangalore	150	500	1.5	5

Results for the high-rise building in the passive house standard

Location	Annual heating demand		
	[kWh/m²a]		
	Swisspacer Ultimate	Stainless steel spacer bar	Aluminium spacer bar
Frankfurt	Evaluation not possible.		
Helsinki	Evaluation not possible.		
	Annual cooling demand		
	[kWh/m²a]		
	Swisspacer Ultimate	Stainless steel spacer bar	Aluminium spacer bar
Bangalore	Evaluation not possible.		

Location	Savings			
	Heat energy			
	[%]		kWh/(m*a)	
	SWS U vs stainless steel	SWS U vs Alu	SWS U vs stainless steel	SWS U vs Alu
Frankfurt	Evaluation not possible		1.59	5.25
Helsinki	Evaluation not possible		2.55	9.3
	Cooling energy			
	[%]		kWh/(m*a)	
	SWS U vs stainless steel	SWS U vs Alu	SWS U vs stainless steel	SWS U vs Alu
Bangalore	Evaluation not possible		1.1	3.72

Location	Savings					
	CO_2					
	[kg CO_2 eq/a]		[(km Go F VI 1.6 TDI)/a]		[kg CO2eq/(m*a)] (assumed from the passive house)	
	SWS U vs stainless steel	SWS U vs Alu	SWS U vs stainless steel	SWS U vs Alu	SWS U vs stainless steel	SWS U vs Alu
Frankfurt	495	1515	4160	12731	0.42	1.4
Helsinki	853	3151	7168	26479	0.78	2.88
Bangalore	453	1574	3807	13227	0.41	1.44

Location	Savings			
	Monetary			
	[€/40a]		[€/ (linear metre of glass edge x 40a)] (assumed from the passive house model)	
	SWS U vs stainless steel	SWS U vs Alu	SWS U vs stainless steel	SWS U vs Alu
Frankfurt	6889	22769	6	21
Helsinki	6754	24670	6	23
Bangalore	1618	5558	1.5	5

Results for the double glazed low-energy house

Location	Annual heating demand		
	[kWh/m²a]		
	Swisspacer Ultimate	Stainless steel spacer bar	Aluminium spacer bar
Frankfurt	53.6	54.8	56.8
Helsinki	100.4	102.3	105.5
	Annual cooling demand		
	[kWh/m²a]		
	Swisspacer Ultimate	Stainless steel spacer bar	Aluminium spacer bar
Bangalore	87.4	88	89.1

Location	Savings			
	Heat energy			
	[%]		kWh/(m*a)	
	SWS U vs stainless steel	SWS U vs Alu	SWS U vs stainless steel	SWS U vs Alu
Frankfurt	3.5%	5.6%	1.89	5.08
Helsinki	3.0%	4.8%	2.95	7.93
	Cooling energy			
	[%]		kWh/(m*a)	
	SWS U vs stainless steel	SWS U vs Alu	SWS U vs stainless steel	SWS U vs Alu
Bangalore	1.2%	1.9%	1.03	1.05

Location	Savings					
	CO_2					
	[kg CO_2 eq/a]		[(km Go F VI 1.6 TDI)/a]		[kg CO2eq/(m*a)] (assumed from the passive house)	
	SWS U vs stainless steel	SWS U vs Alu	SWS U vs stainless steel	SWS U vs Alu	SWS U vs stainless steel	SWS U vs Alu
Frankfurt	51	138	429	1160	0.51	1.39
Helsinki	96	257	807	2160	0.97	2.59
Bangalore	39	104	328	874	0.39	1.05

Location	Savings			
	Monetary			
	[€/40a]		[€/ (linear metre of glass edge x 40a)] (assumed from the passive house model)	
	SWS U vs stainless steel	SWS U vs Alu	SWS U vs stainless steel	SWS U vs Alu
Frankfurt	690	1854	6.96	18.71
Helsinki	630	1690	6.36	17.05
Bangalore	140	376	1.41	3.79

Results for the triple glazed low-energy house

Location	Annual heating demand		
	[kWh/m²a]		
	Swisspacer Ultimate	Stainless steel spacer bar	Aluminium spacer bar
Frankfurt	45.9	47.1	50.2
Helsinki	87.9	89.9	94.6
	Annual cooling demand		
	[kWh/m²a]		
	Swisspacer Ultimate	Stainless steel spacer bar	Aluminium spacer bar
Bangalore	82.1	82.8	84.5

Location	Savings			
	Heat energy			
	[%]		kWh/(m*a)	
	SWS U vs stainless steel	SWS U vs Alu	SWS U vs stainless steel	SWS U vs Alu
Frankfurt	6.2%	8.6%	1.96	6.75
Helsinki	5.0%	7.1%	3.07	10.58
	Cooling energy			
	[%]		kWh/(m*a)	
	SWS U vs stainless steel	SWS U vs Alu	SWS U vs stainless steel	SWS U vs Alu
Bangalore	2.0%	2.8%	1.08	149

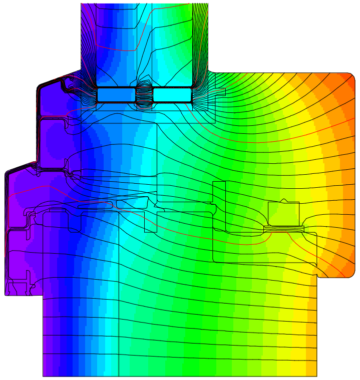
Location	Savings					
	CO_2					
	[kg CO_2 eq/a]		[(km Go F VI 1.6 TDI)/a]		[kg CO2eq/(m*a)] (assumed from the passive house)	
	SWS U vs stainless steel	SWS U vs Alu	SWS U vs stainless steel	SWS U vs Alu	SWS U vs stainless steel	SWS U vs Alu
Frankfurt	53	183	445	1538	0.53	1.85
Helsinki	100	343	840	2882	1.01	3.46
Bangalore	44	143	370	1202	0.44	1.44

Location	Savings			
	Monetary			
	[€/40a]		[€/ (linear metre of glass edge x 40a)] (assumed from the passive house model)	
	SWS U vs stainless steel	SWS U vs Alu	SWS U vs stainless steel	SWS U vs Alu
Frankfurt	715	2463	7.21	24.85
Helsinki	655	2255	6.61	22.75
Bangalore	147	504	1.48	5.09

6 Appendix

Passive House Institute

Appendix 1 - Determination of frame-U-values and glass edge losses



Because a separate heating system is not necessarily required in Passive Houses, high demands are placed on the quality of the building components used. The colder the climate, the higher the requirements on the components. To cover this, PHI has identified regions of similar requirements, and defined certification criteria. These criteria are available for free download at the website of the Passive House Institute.

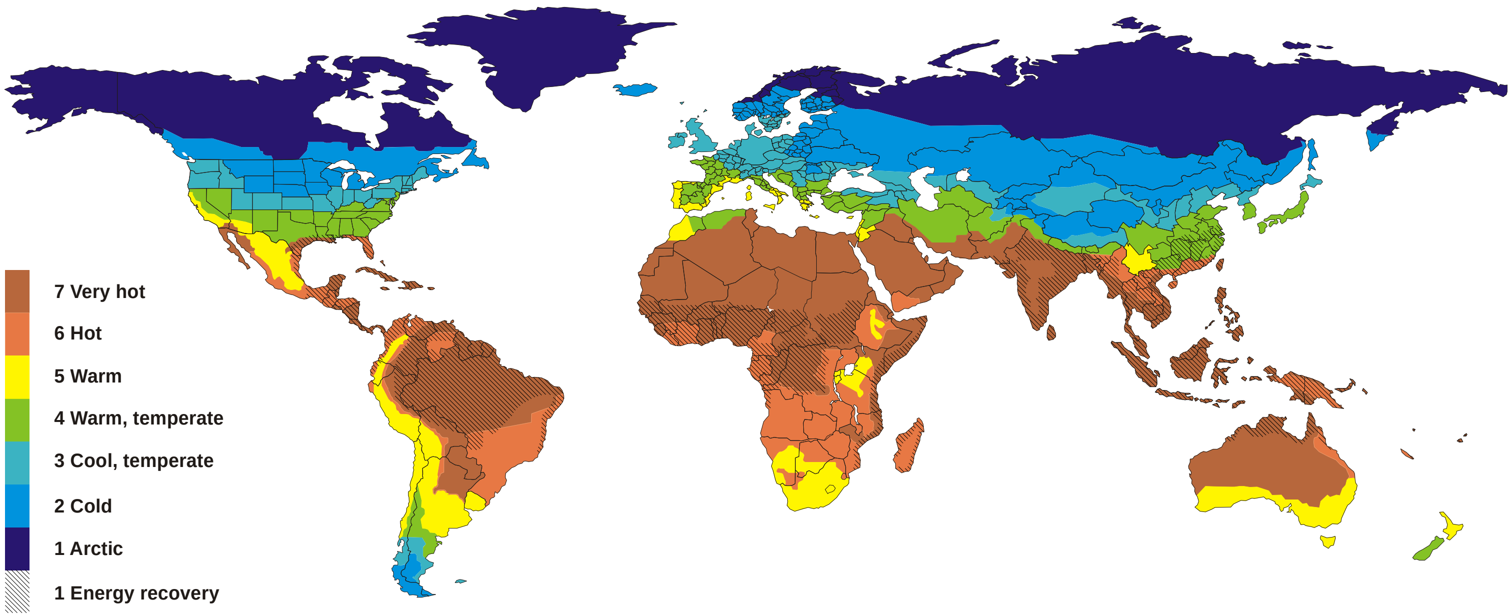
Beside the thermal transmittance of the installed window, the achieving of the hygiene criterion is crucial. For reasons of hygiene, this criterion limits the minimum individual temperature on window surfaces to prevent condensate and mold growth. As a rule of thumb, this minimum temperature occurs at the glass edge and is essentially influenced by the used edge bond.

For the several climate regions, the Passive House Institute has defined the following requirements regarding the temperature factor $\mathbf{f}_{Rsi=0,25\ m^2K/W}$: Arctic: 0.80; cold: 0.75; cool-temperate: 0.70; warm-temperate: 0.65; warm: 0.55. An edge bond suits to a climate region, if minimum three of the reference frames, shown in this report are fulfilling the requirement of the specific climate region with the edge bond to be tested.

Passivhäuser stellen aufgrund der Möglichkeit, auf ein separates Heizsystem zu verzichten, hohe Anforderungen an die Qualität der verwendeten Bauteile. Dabei steigen die Anforderungen, je kälter das Klima ist. Darum hat das Passivhaus Institut Regionen gleicher Anforderung identifiziert und für diese Zertifizierungskriterien festgelegt. Die Kriterien sind auf der Homepage des Passivhaus Instituts als kostenfreier Download verfügbar.

Neben dem Wärmedurchgangskoeffizienten des eingebauten Fensters ist die Einhaltung des Hygienekriteriums entscheidend. Dieses Kriterium begrenzt die minimale Einzeltemperatur an der Innenseite der Fensteroberfläche, um Tauwasserausfall und Schimmelbildung zu vermeiden. In der Regel tritt die minimale Einzeltemperatur im Bereich des Glasrandes auf, wo sie wesentlich durch den verwendeten Abstandhalter beeinflusst wird.

Das Passivhaus Institut hat für die Klimaregionen folgende Anforderungen an den minimalen Temperaturfaktor $\mathbf{f}_{Rsi=0,25\ m^2K/W}$ festgelegt: Arktisch: 0,80; Kalt: 0,75; Kühl-gemäßigt: 0,70; Warm-gemäßigt: 0,65; Warm: 0,55. Ein Abstandhalter ist für eine Klimaregion geeignet, wenn mindestens drei der in diesem Bericht dargestellten Referenzrahmen unter Verwendung des zu prüfenden Abstandhalters die Anforderung an den Temperaturfaktor der jeweiligen Klasse erfüllen.



Certified edge bonds are ranked by so called Edge Resistance RE in **efficiency classes.** The Edge resistance includes the thermal tansmittance of the secondary seal, the spacer itself and a gas box, each with its specific hights. Regarding the thermal transmittance, the Passive House Institute uses the thermal transmittance determined according to WA 17/1 of the ift Rosenheim.

The sum of the height of the 3 boxes is always constant. For the height of the secondary seal and the spacer is determined, the height of the gas box is variable. The thermal transmittance of the gas box equates to a glazing with U_g = 0.70 W/(m²K) at a glass package of 4/18/4/18/4 mm.

The **simulation of the thermal values** of the frame sections were based on the regulations of the standard ISO 10077-1:2010 and 10077-2:2012. In case of one glazing, the models are 40 cm, in case of 2 glazing 60 cm in hight.

For modeling and simulations, the software Flixo 7 of Infomind was used. For the used **boundary conditions**, please have a look at following drawings and tables.

Zertifizierte Abstandhalter werden abhängig von dem Kantenwiderstand RE in **Effizienzklassen** eingestuft. In den Kantenwiderstand gehen die Wärmeleitfähigkeit der Sekundärdichtung, die Wärmeleitfähigkeit des Abstandhalters sowie die Wärmeleitfähigkeit einer Gasbox mit ihren jeweiligen Höhen ein. Bezüglich der Wärmeleitfähigkeit des Abstandhalters greift das Passivhaus Institut auf die nach ift-Richtlinie WA 17/1 ermittelten Kennwerte zurück.

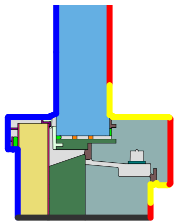
Die Summe der Höhen der 3 Boxen ist stets gleich, die Höhen des Abstandhalters sowie der Sekundärdichtdichtung sind definiert, damit ist die Höhe der Gasbox variabel. Die Wärmeleitfähigkeit dieser Box entspricht einer Verglasung mit U_g = 0,70 W/(m²K) bei dem Scheibenaufbau 4/18/4/18/4.

Die **Berechnung der thermischen Kennwerte** der Rahmenschnitte erfolgte auf der Grundlage der ISO 10077-1:2010 und 10077-2:2012.Dabei sind die Modelle mit einem Glasteil stets 40 cm, Modelle mit 2 Glasteilen stets 60 cm hoch.

Zur Bildung der Modelle und zur Berechnung der Wärmeströme wurde das Programm Flixo 7 Professional der Firma Infomind genutzt. Die **Randbedingungen** wurden wie unten gezeigt angesetzt.

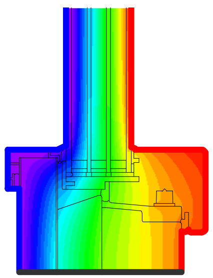
$$R_E = \frac{\Sigma h}{\lambda_{Box1} \cdot h_{Box1} + \lambda_{Box2} \cdot h_{Box2} + \lambda_{Gas} \cdot h_{Gas}}$$

Edge Resistance R_E	Passive house efficiency class	Name
≥ 1.5 mK/W	ph**C**	Certifiable component
≥ 3.0 mK/W	ph**B**	Basic component
≥ 4.5 mK/W	ph**A**	Advanced component

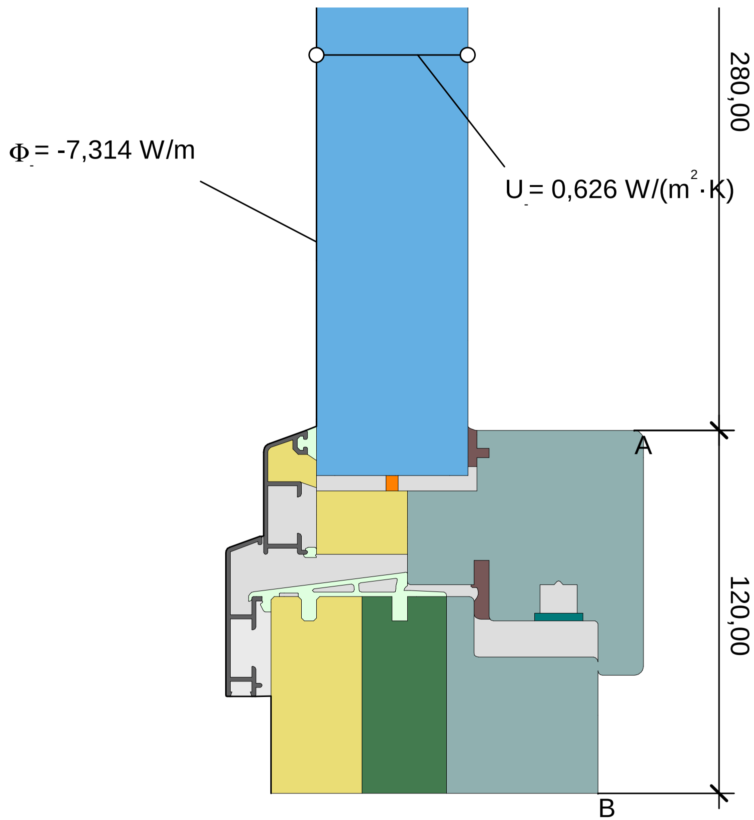


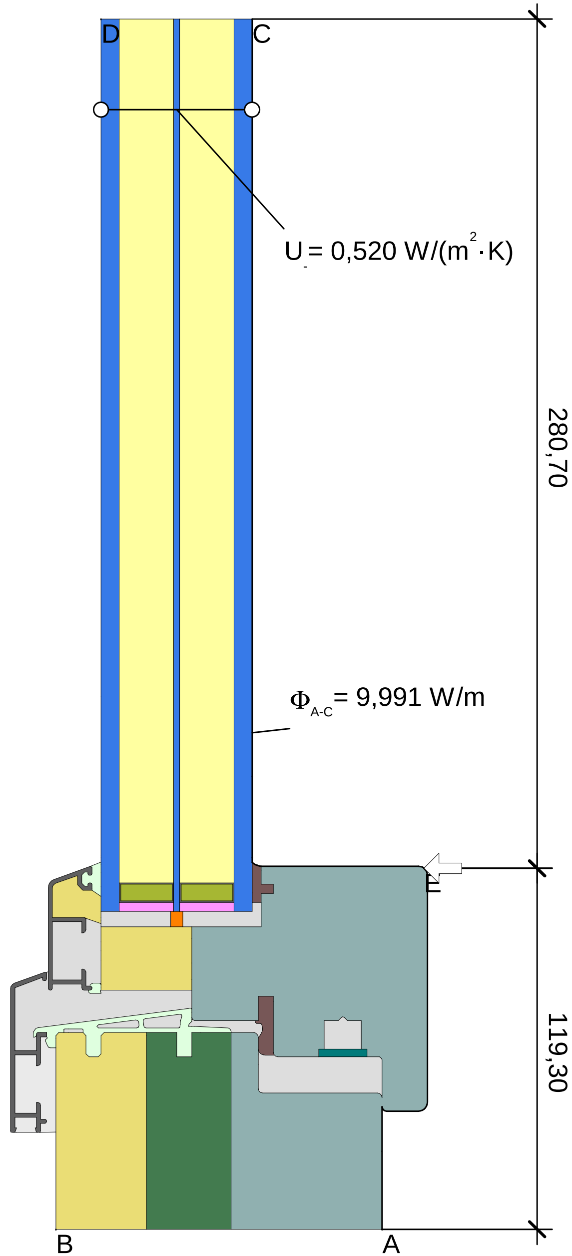
Randbedingung	q[W/m²]	θ[°C]	R[(m²·K)/W]	ε
Adiabatic	0,000			
Exterior I Außen		-10,000	0,040	
e 0,9 Cavity I Hohlraum				0,900
fRsi: Interior I Innen		20,000	0,250	

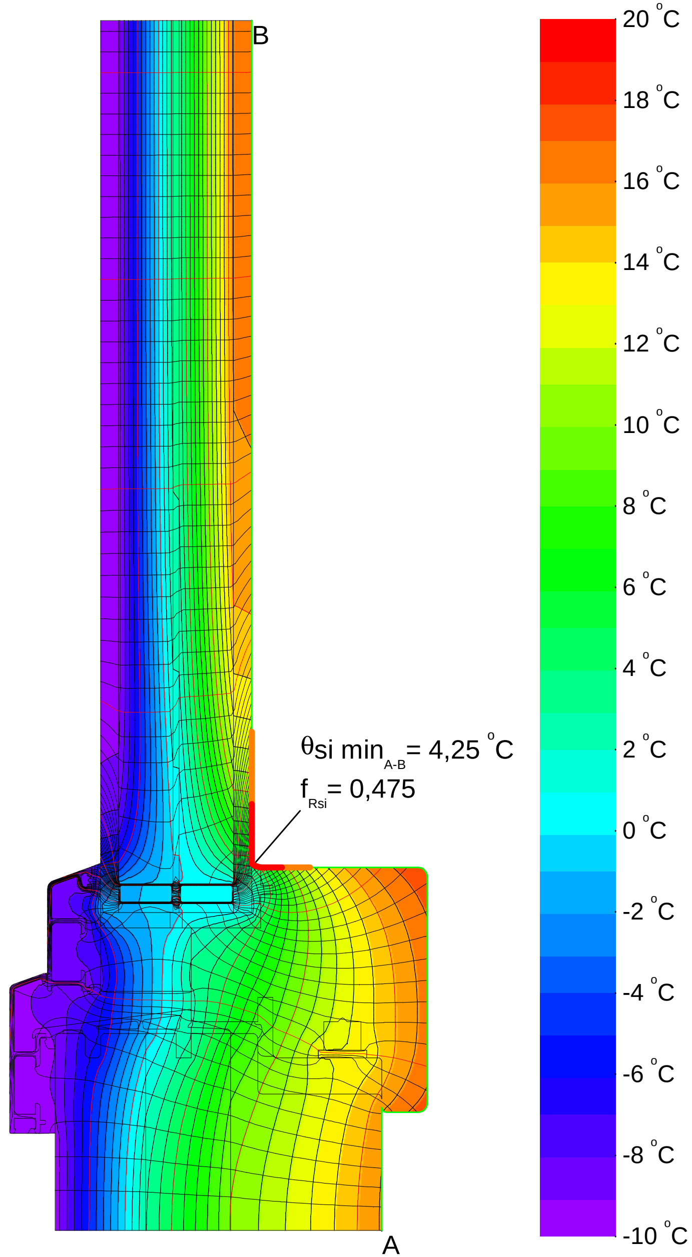
Randbedingung	q[W/m²]	θ[°C]	R[(m²·K)/W]	ε
Adiabatic	0,000			
Exterior I Außen		-10,000	0,040	
Innen Fensterrahmen Reduziert		20,000	0,200	
Innen Fensterrahmen Standard		20,000	0,130	
e 0,9 Cavity I Hohlraum				0,900



Material	λ[W/(m·K)]	ε
Aluminum I Aluminium 10456	160,000	0,900
Ar18 in 50 mm U 0,52	0,021	
ENERfoam	0,040	
EPDM	0,250	0,900
Glass I Glas	1,000	0,900
Insulation I Wärmedämmung 022	0,022	0,900
Insulation I Wärmedämmung 040	0,040	0,900
Polysulfid (1)	0,400	0,900
Silicagel (Trockenmittel) (1)	0,130	
Soft-PVC I Weich-PVC	0,140	0,900
Spruce Fir I Fichte, Tanne	0,110	0,900
Steel I Stahl	50,000	0,900
Unvent. cavity I unbel. Hohlr.		
slightly vent. cav. I leicht bel. Hohlr.		







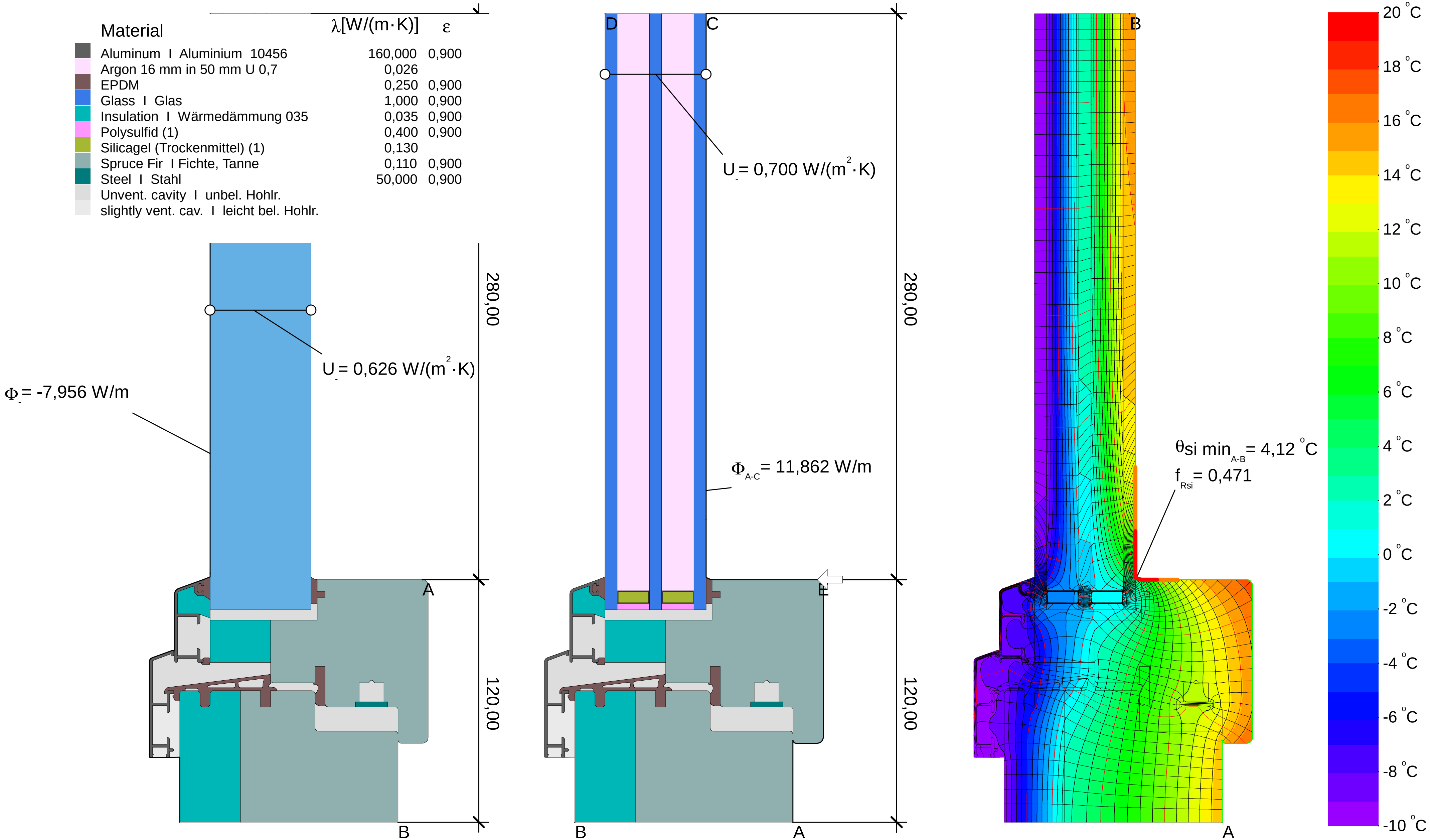
$$\Psi_{A\text{-}E\text{-}C,*} = \frac{\Phi}{\Delta T} - U_1 \cdot b_1 - U_2 \cdot b_2 = \frac{9{,}991}{30{,}000} - 0{,}572 \cdot 0{,}119 - 0{,}520 \cdot 0{,}281 = 0{,}119 \text{ W/(m·K)}$$

$$U_{f\,A,B} = \frac{\frac{\Phi}{\Delta T} - U_p \cdot b_p}{b_f} = \frac{\frac{7{,}314}{30{,}000} - 0{,}626 \cdot 0{,}280}{0{,}120} = 0{,}572 \text{ W/(m}^2\text{·K)}$$

Timber-aluminum - Cold

Aluminum spacer

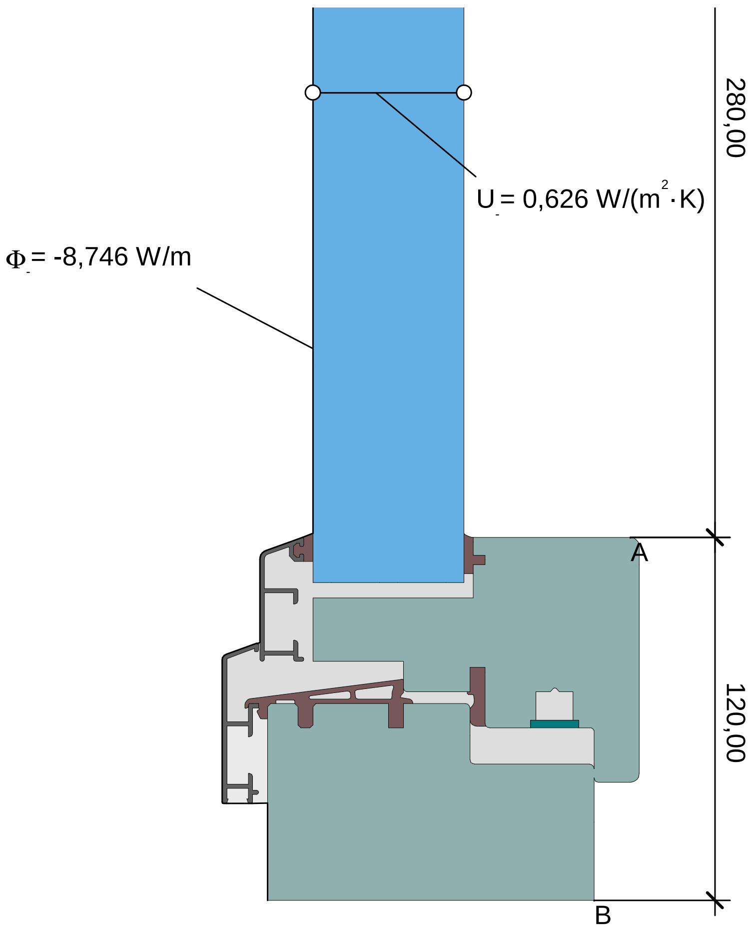
Material	λ[W/(m·K)]	ε
Aluminum I Aluminium 10456	160,000	0,900
Argon 16 mm in 50 mm U 0,7	0,026	
EPDM	0,250	0,900
Glass I Glas	1,000	0,900
Insulation I Wärmedämmung 035	0,035	0,900
Polysulfid (1)	0,400	0,900
Silicagel (Trockenmittel) (1)	0,130	
Spruce Fir I Fichte, Tanne	0,110	0,900
Steel I Stahl	50,000	0,900
Unvent. cavity I unbel. Hohlr.		
slightly vent. cav. I leicht bel. Hohlr.		

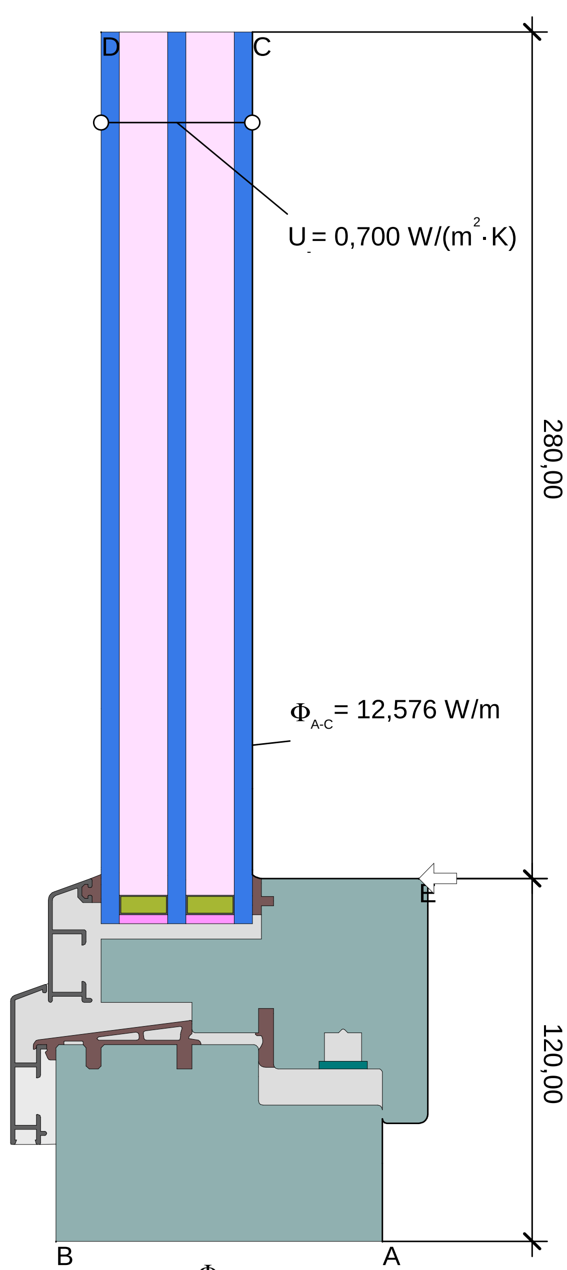


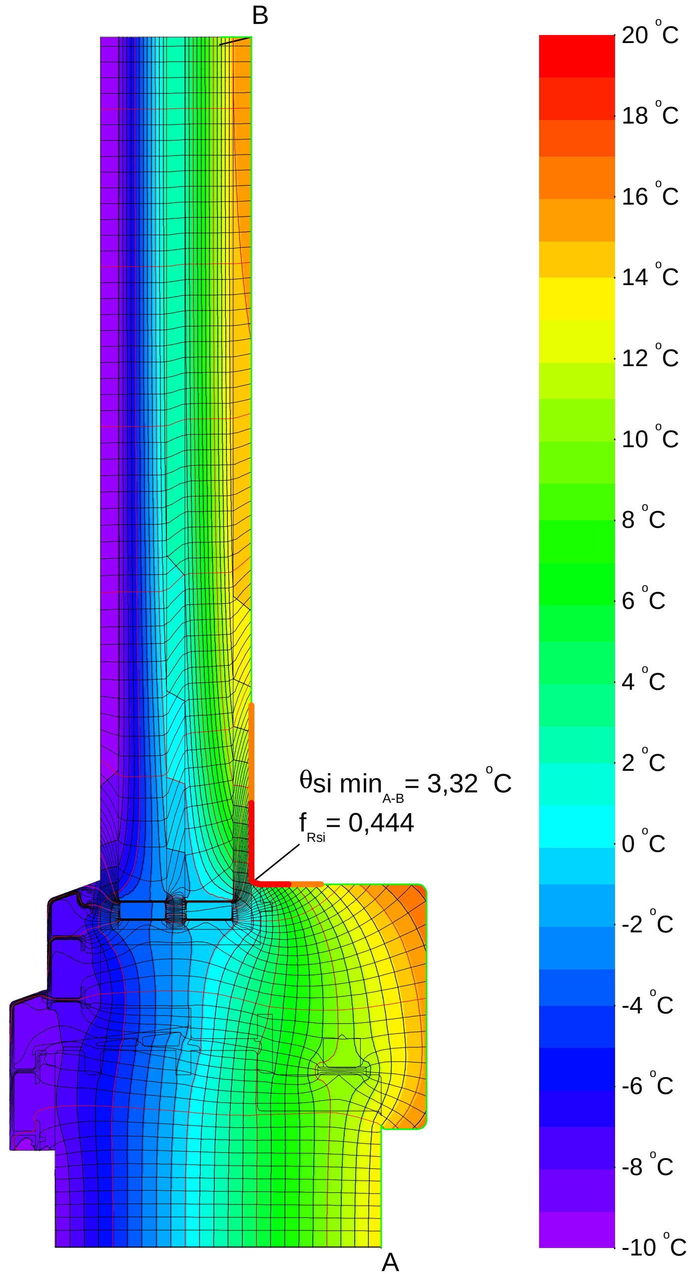
$$U_{f\,A,B} = \frac{\frac{\Phi}{\Delta T} - U_p \cdot b_p}{b_f} = \frac{\frac{7,956}{30,000} - 0,626 \cdot 0,280}{0,120} = 0,750\ W/(m^2 \cdot K)$$

$$\psi_{A\text{-}E\text{-}C,*} = \frac{\Phi}{\Delta T} - U_1 \cdot b_1 - U_2 \cdot b_2 = \frac{11,862}{30,000} - 0,750 \cdot 0,120 - 0,700 \cdot 0,280 = 0,109\ W/(m \cdot K)$$

Material	λ[W/(m·K)]	ε
Aluminum I Aluminium 10456	160,000	0,900
Argon 16 mm in 50 mm U 0,7	0,026	
EPDM	0,250	0,900
Glass I Glas	1,000	0,900
Polysulfid (1)	0,400	0,900
Silicagel (Trockenmittel) (1)	0,130	
Spruce Fir I Fichte, Tanne	0,110	0,900
Steel I Stahl	50,000	0,900
Unvent. cavity I unbel. Hohlr.		
slightly vent. cav. I leicht bel. Hohlr.		





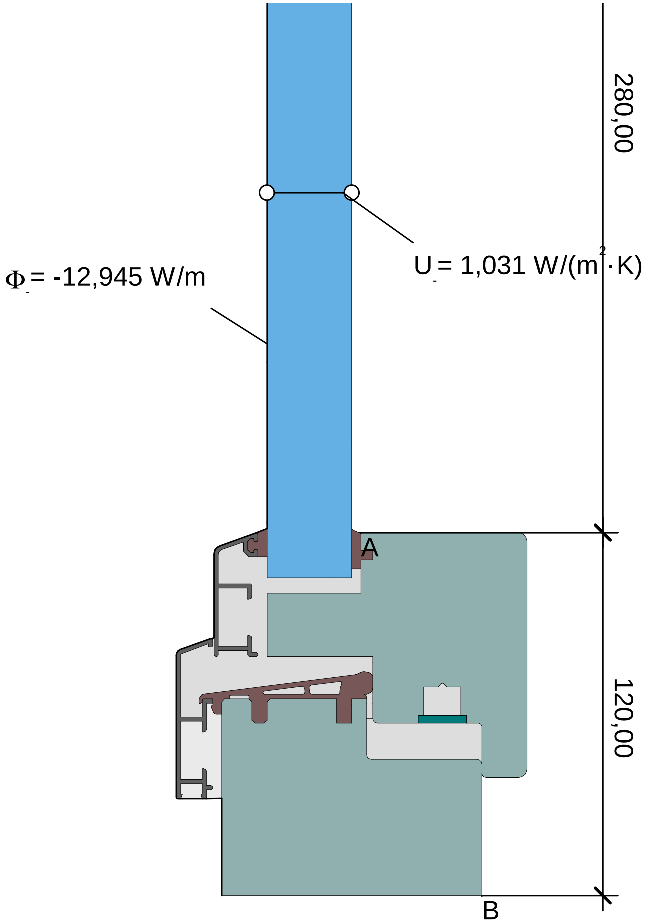


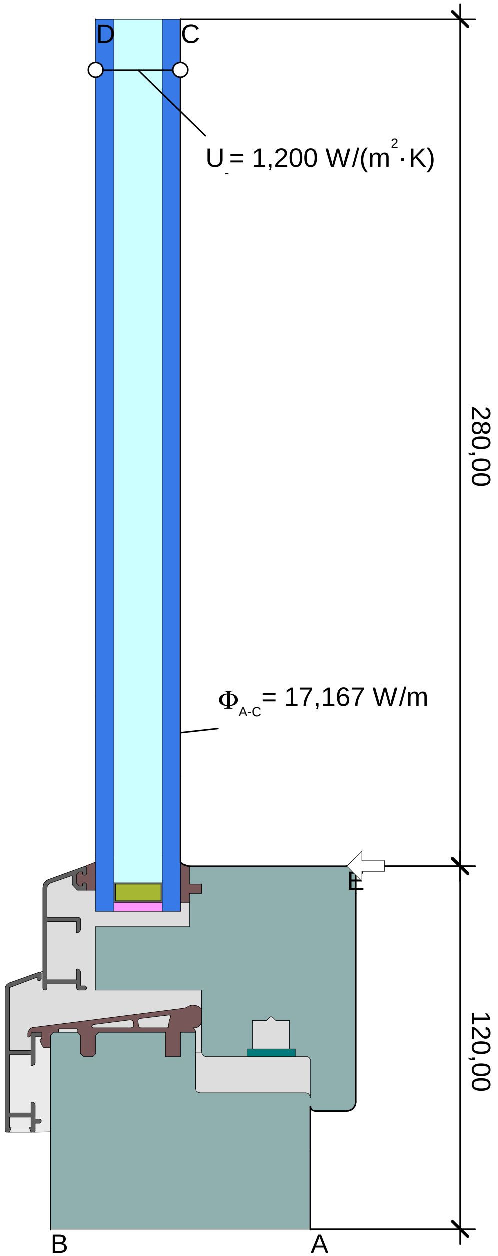
$$\psi_{A\text{-}E\text{-}C,*} = \frac{\Phi}{\Delta T} - U_1 \cdot b_1 - U_2 \cdot b_2 = \frac{12,576}{30,000} - 0,970 \cdot 0,120 - 0,700 \cdot 0,280 = 0,107\ \mathrm{W/(m \cdot K)}$$

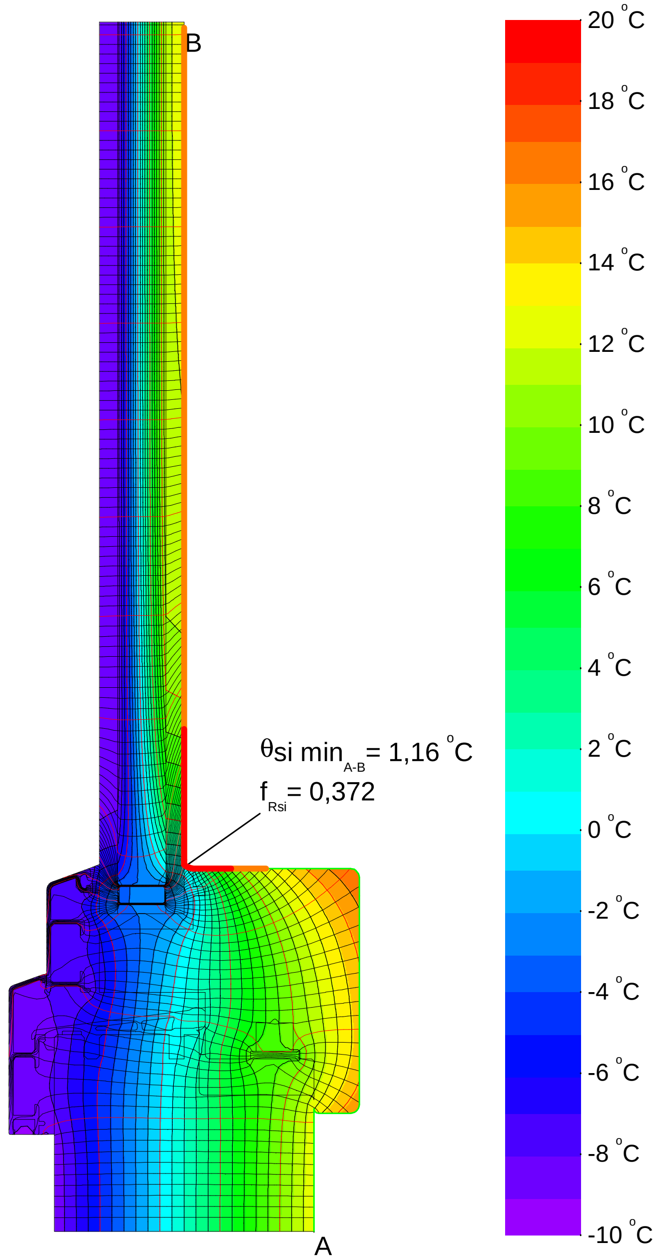
$$U_{f\,A,B} = \frac{\frac{\Phi}{\Delta T} - U_p \cdot b_p}{b_f} = \frac{\frac{8,746}{30,000} - 0,626 \cdot 0,280}{0,120} = 0,970\ \mathrm{W/(m^2 \cdot K)}$$

Timber-aluminum - Warm, temperate **Aluminum spacer**

Material	λ[W/(m·K)]	ε
Aluminum I Aluminium 10456	160,000	0,900
Argon 16 mm in28 mm U 1,2	0,025	
EPDM	0,250	0,900
Glass I Glas	1,000	0,900
Polysulfid (1)	0,400	0,900
Silicagel (Trockenmittel) (1)	0,130	
Spruce Fir I Fichte, Tanne	0,110	0,900
Steel I Stahl	50,000	0,900
Unvent. cavity I unbel. Hohlr.		
slightly vent. cav. I leicht bel. Hohlr.		



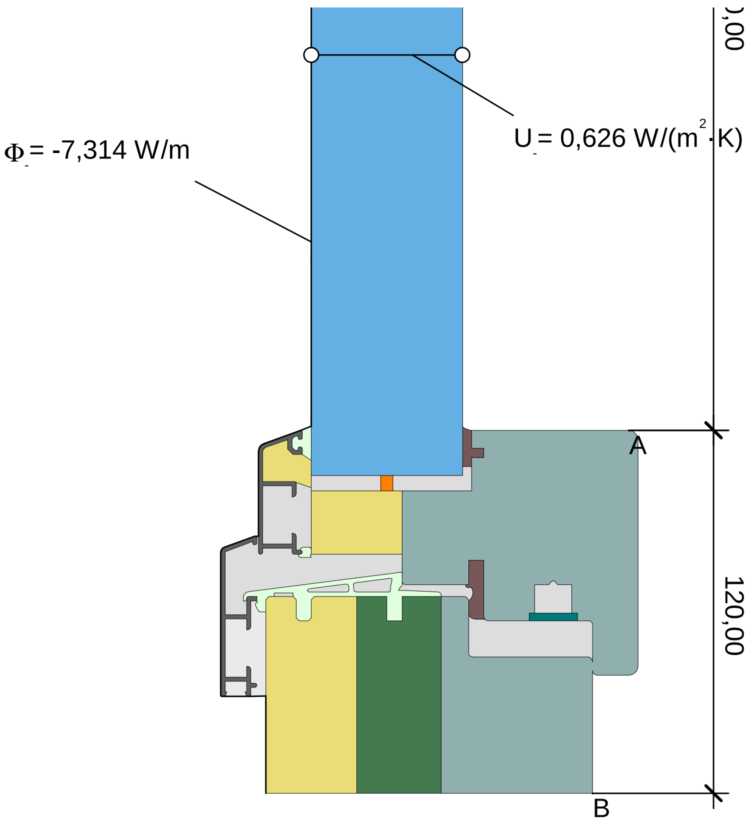


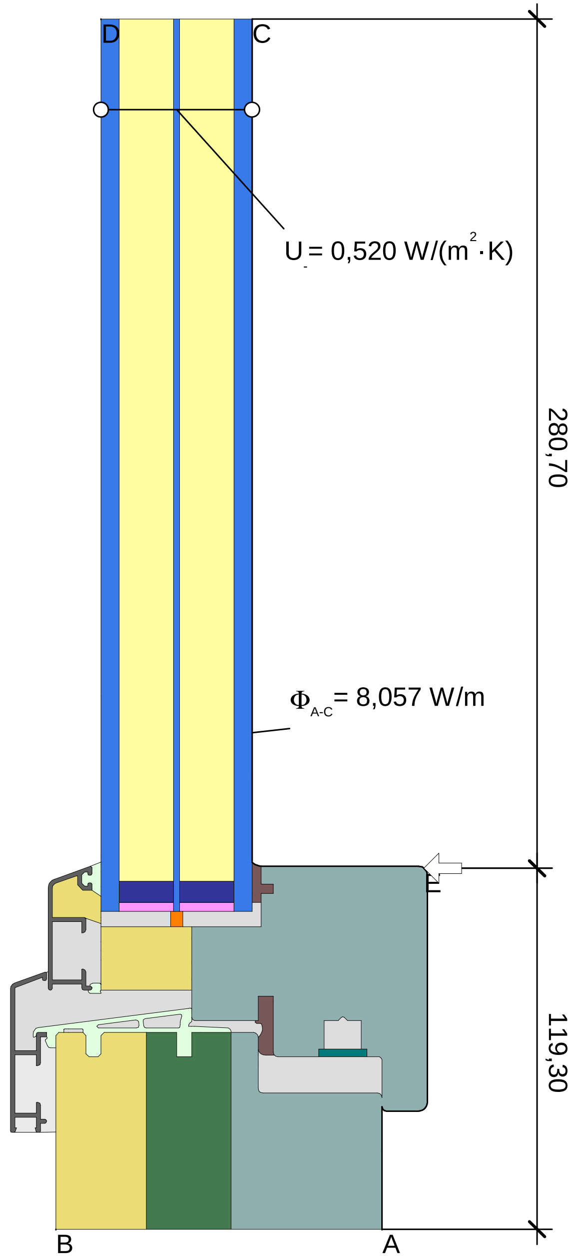


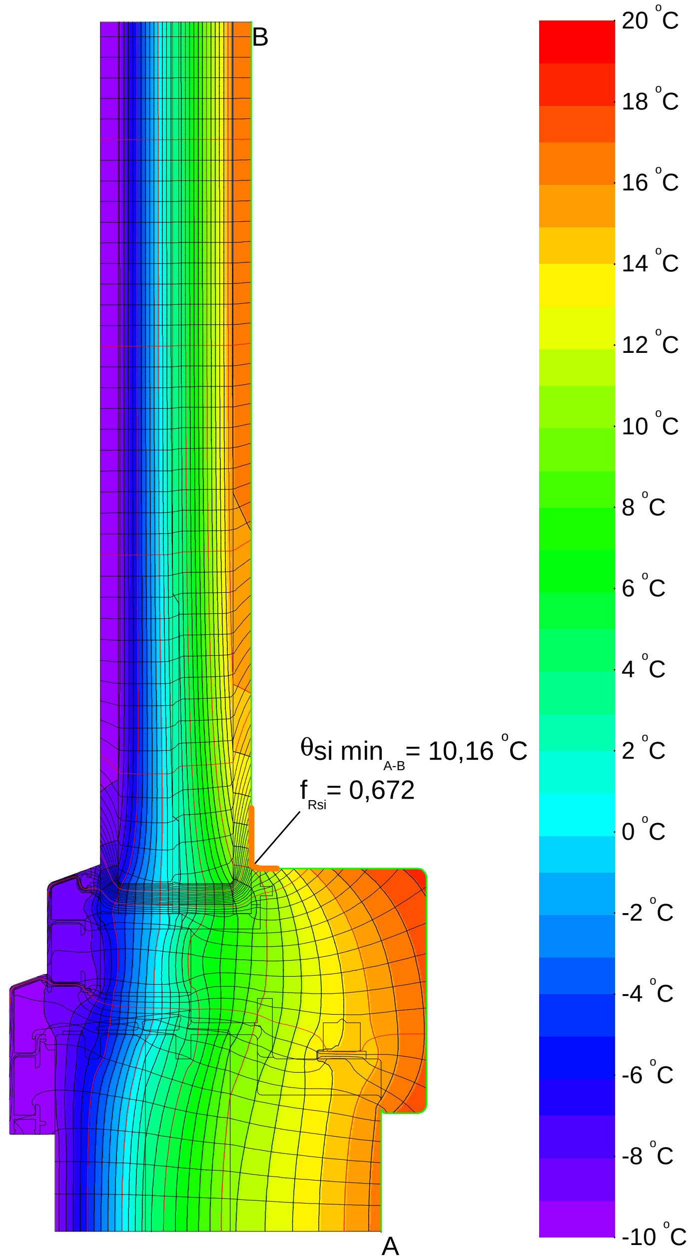
$$\psi_{A\text{-}E\text{-}C,*} = \frac{\Phi}{\Delta T} - U_1 \cdot b_1 - U_2 \cdot b_2 = \frac{17{,}167}{30{,}000} - 1{,}190 \cdot 0{,}120 - 1{,}200 \cdot 0{,}280 = 0{,}093 \text{ W/(m·K)}$$

$$U_{f\,A,B} = \frac{\frac{\Phi}{\Delta T} - U_p \cdot b_p}{b_f} = \frac{\frac{12{,}945}{30{,}000} - 1{,}031 \cdot 0{,}280}{0{,}120} = 1{,}190 \text{ W/(m}^2\text{·K)}$$

Material	λ[W/(m·K)]	ε
Aluminum I Aluminium 10456	160,000	0,900
Ar18 in 50 mm U 0,52	0,021	
ENERfoam	0,040	
EPDM	0,250	0,900
Glass I Glas	1,000	0,900
Insulation I Wärmedämmung 022	0,022	0,900
Insulation I Wärmedämmung 040	0,040	0,900
Polysulfid (1)	0,400	0,900
Edelstahl Abstandhalter	0,610	
Soft-PVC I Weich-PVC	0,140	0,900
Spruce Fir I Fichte, Tanne	0,110	0,900
Steel I Stahl	50,000	0,900
Unvent. cavity I unbel. Hohlr.		
slightly vent. cav. I leicht bel. Hohlr.		







$$\psi_{A\text{-}E\text{-}C,*} = \frac{\Phi}{\Delta T} - U_1 \cdot b_1 - U_2 \cdot b_2 = \frac{8{,}057}{30{,}000} - 0{,}572 \cdot 0{,}119 - 0{,}520 \cdot 0{,}281 = 0{,}054 \text{ W/(m·K)}$$

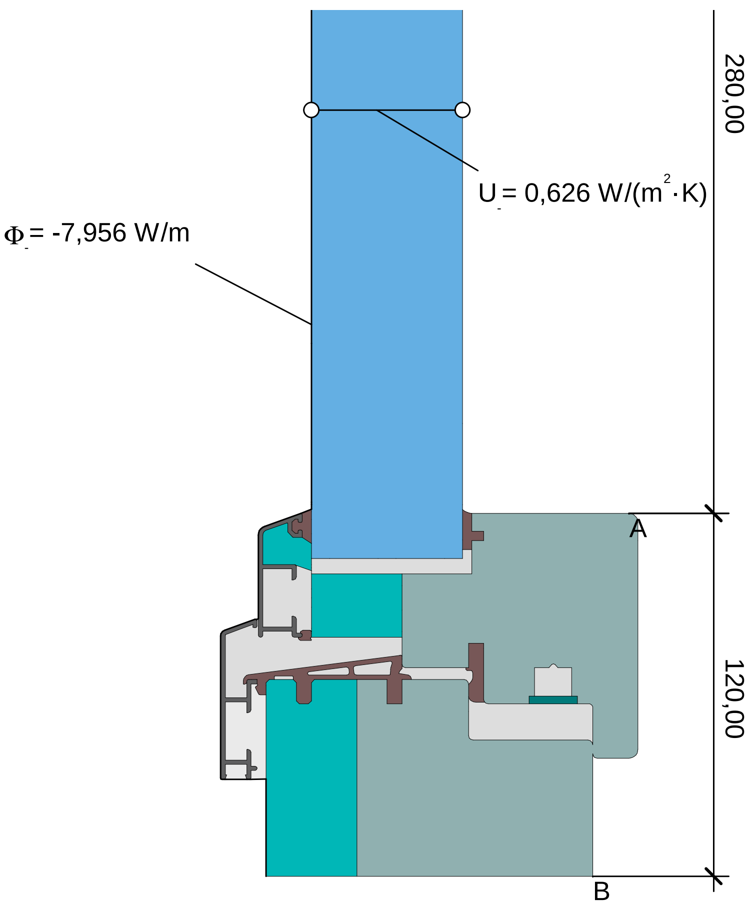
$$U_{f\,A,B} = \frac{\frac{\Phi}{\Delta T} - U_p \cdot b_p}{b_f} = \frac{\frac{7{,}314}{30{,}000} - 0{,}626 \cdot 0{,}280}{0{,}120} = 0{,}572 \text{ W/(m}^2\text{·K)}$$

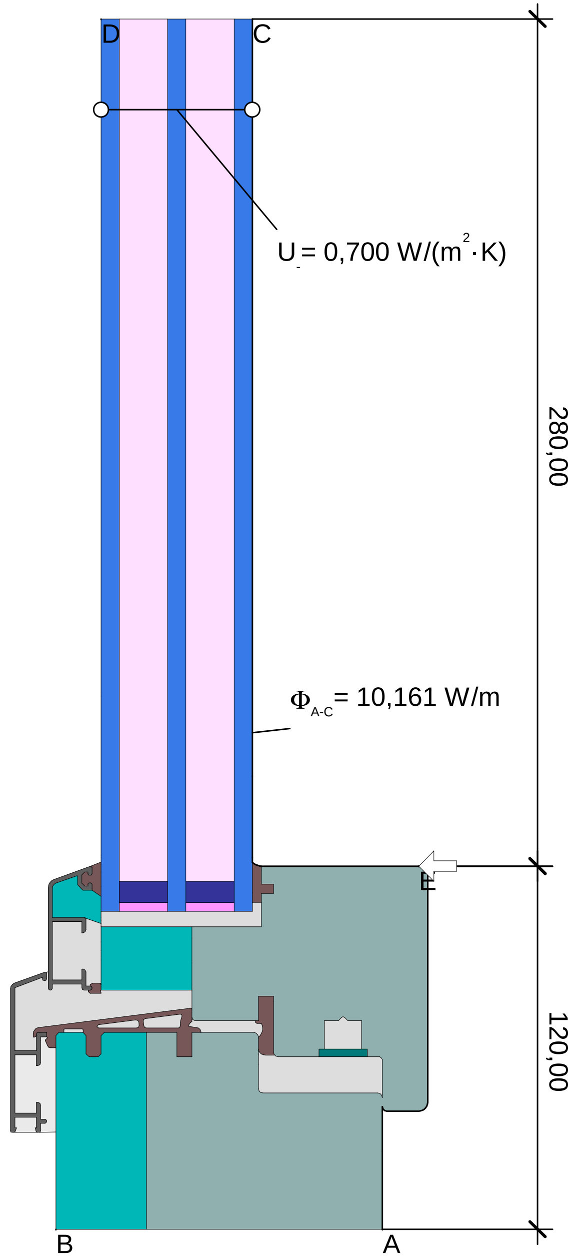
Timber-aluminum - Cold

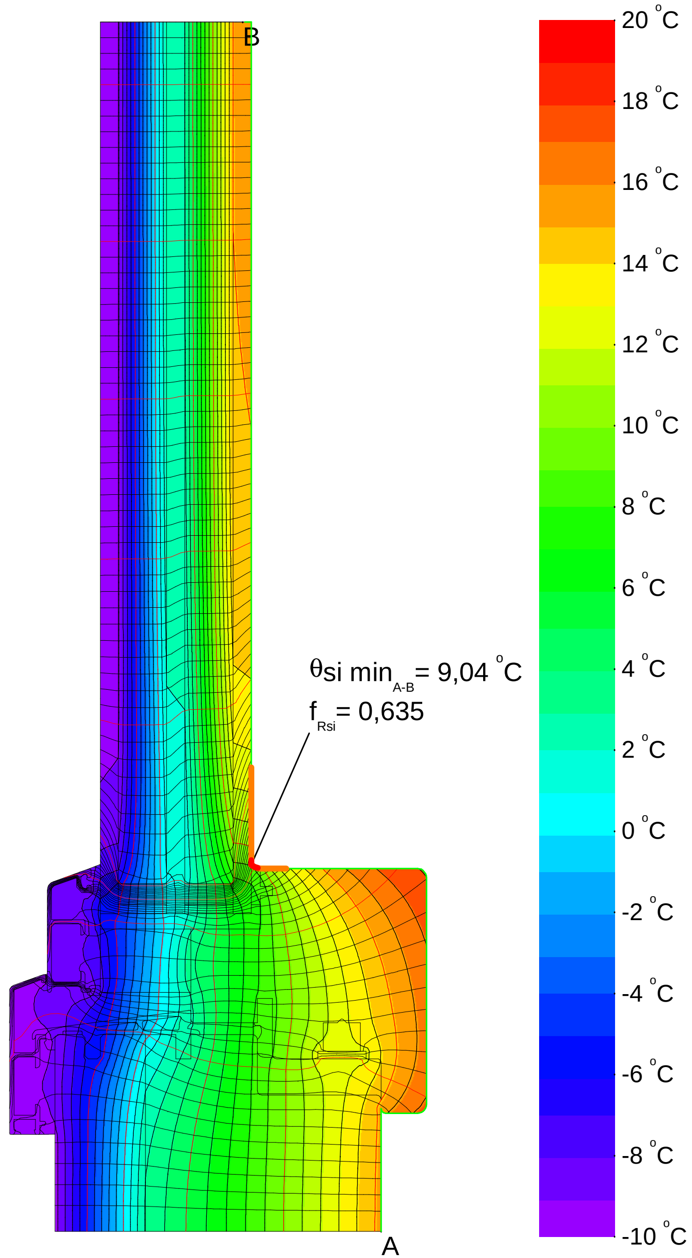
Stainless steel spacer

Passive House Institute

Material	λ[W/(m·K)]	ε
Aluminum I Aluminium 10456	160,000	0,900
Argon 16 mm in 50 mm U 0,7	0,026	
EPDM	0,250	0,900
Glass I Glas	1,000	0,900
Insulation I Wärmedämmung 035	0,035	0,900
Polysulfid (1)	0,400	0,900
Edelstahl Abstandhalter	0,610	
Spruce Fir I Fichte, Tanne	0,110	0,900
Steel I Stahl	50,000	0,900
Unvent. cavity I unbel. Hohlr.		
slightly vent. cav. I leicht bel. Hohlr.		







$$U_{f\,A,B} = \frac{\frac{\Phi}{\Delta T} - U_p \cdot b_p}{b_f} = \frac{\frac{7,956}{30,000} - 0,626 \cdot 0,280}{0,120} = 0,750\ W/(m^2 \cdot K)$$

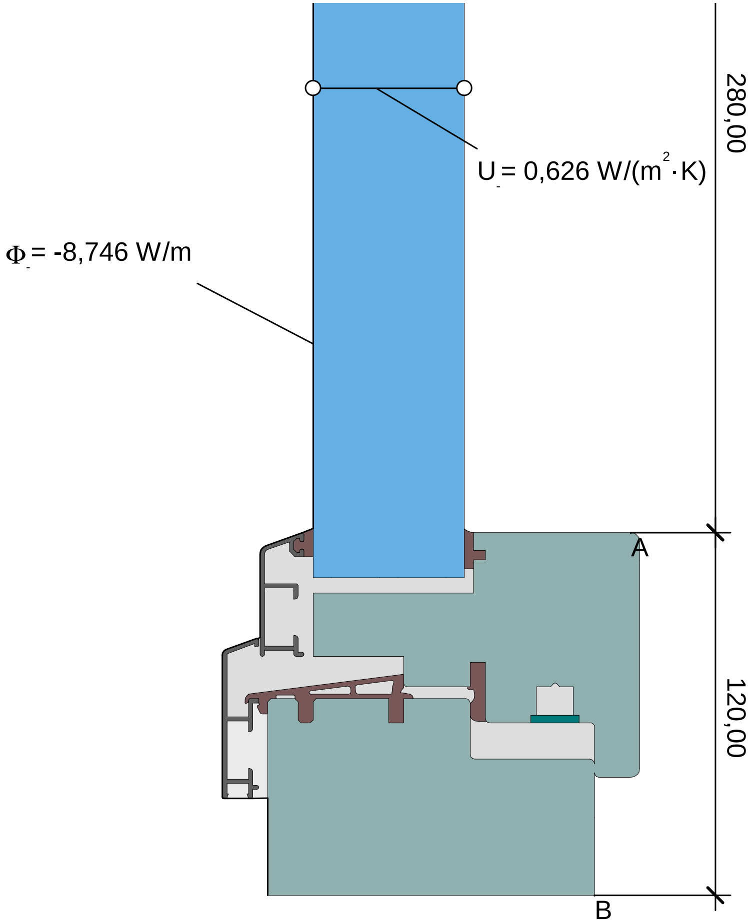
$$\Psi_{A\text{-}E\text{-}C,*} = \frac{\Phi}{\Delta T} - U_1 \cdot b_1 - U_2 \cdot b_2 = \frac{10,161}{30,000} - 0,750 \cdot 0,120 - 0,700 \cdot 0,280 = 0,053\ W/(m \cdot K)$$

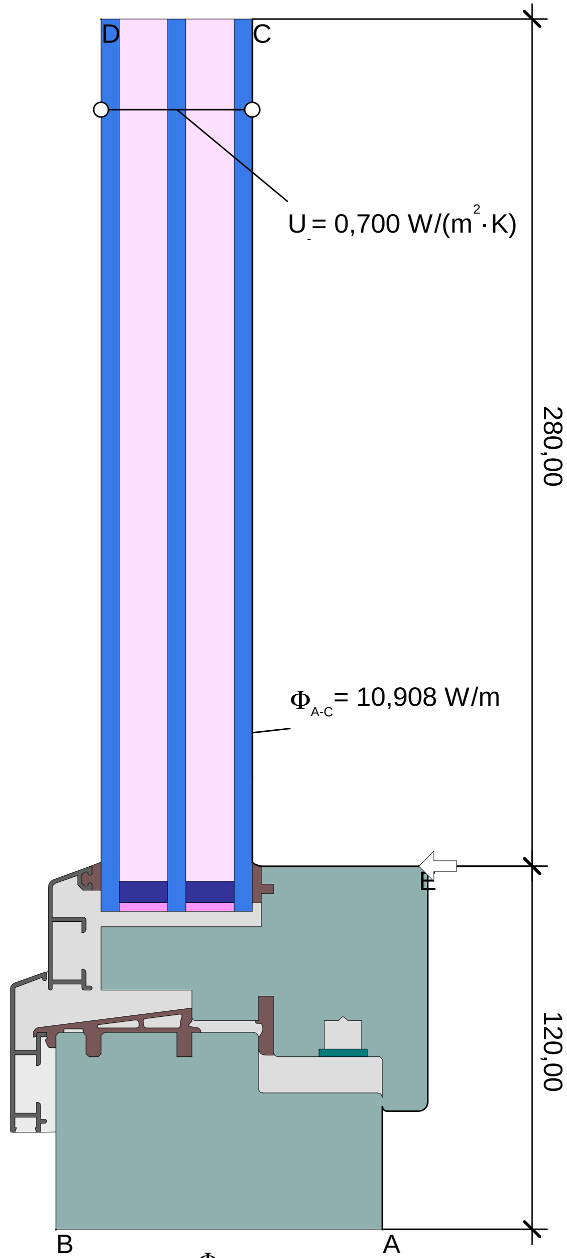
Timber-aluminum - Cool, temperate

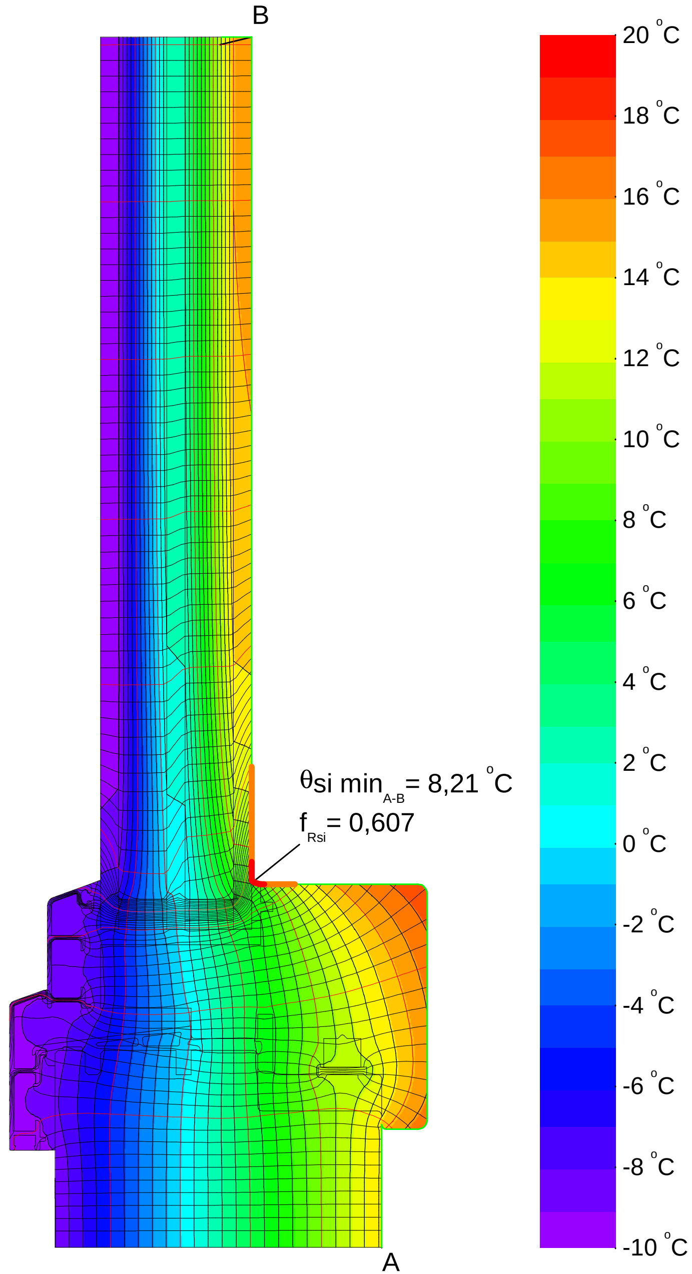
Stainless steel spacer

Passive House Institute

Material	λ[W/(m·K)]	ε
Aluminum I Aluminium 10456	160,000	0,900
Argon 16 mm in 50 mm U 0,7	0,026	
EPDM	0,250	0,900
Glass I Glas	1,000	0,900
Polysulfid (1)	0,400	0,900
Edelstahl Abstandhalter	0,610	
Spruce Fir I Fichte, Tanne	0,110	0,900
Steel I Stahl	50,000	0,900
Unvent. cavity I unbel. Hohlr.		
slightly vent. cav. I leicht bel. Hohlr.		







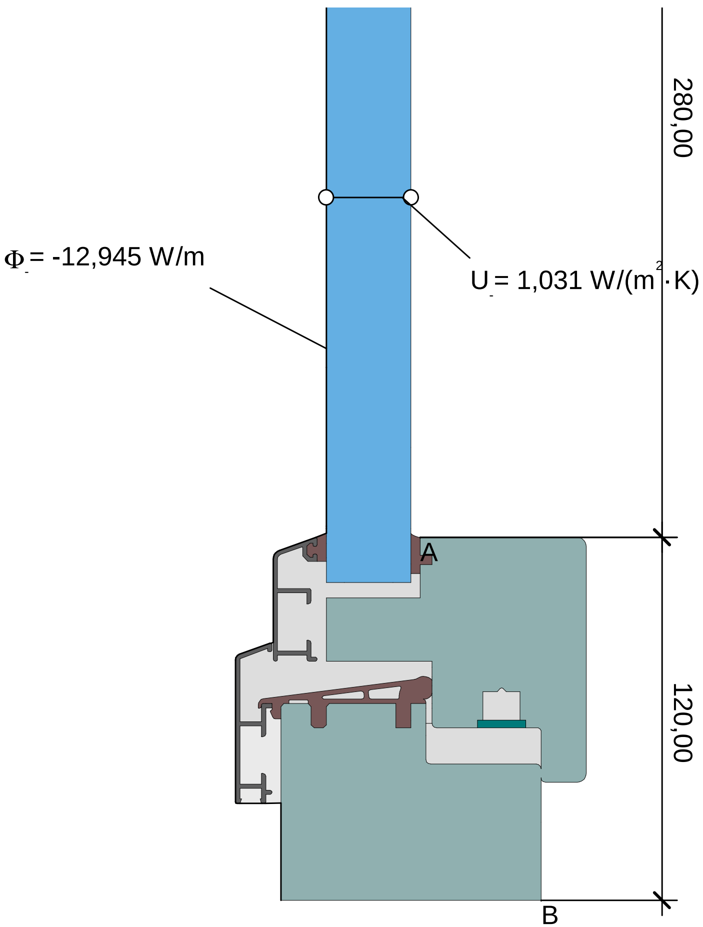
$$\psi_{A\text{-}E\text{-}C,*} = \frac{\Phi}{\Delta T} - U_1 \cdot b_1 - U_2 \cdot b_2 = \frac{10,908}{30,000} - 0,970 \cdot 0,120 - 0,700 \cdot 0,280 = 0,051\ W/(m \cdot K)$$

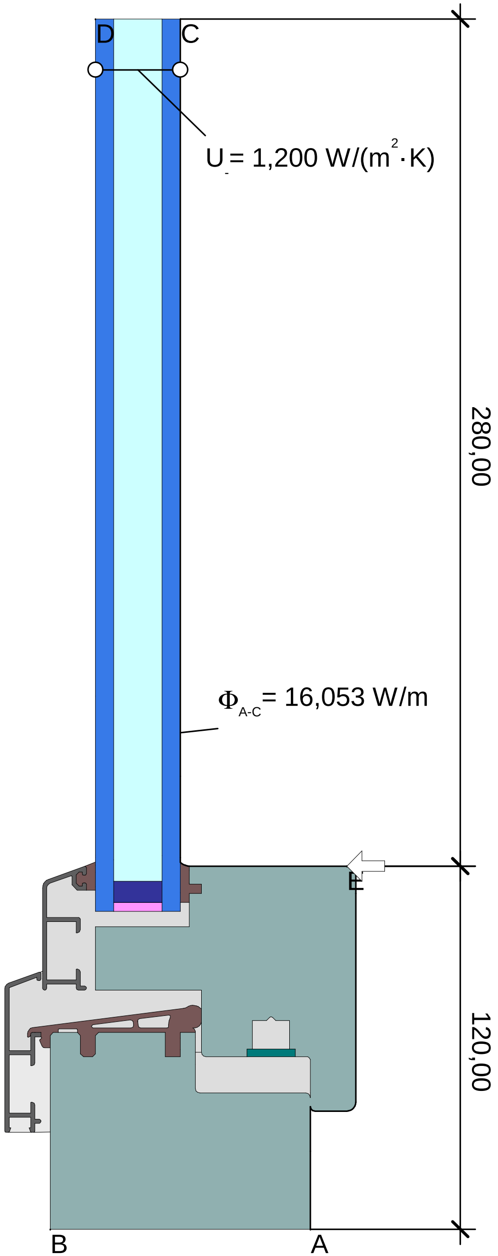
$$U_{f\,A,B} = \frac{\frac{\Phi}{\Delta T} - U_p \cdot b_p}{b_f} = \frac{\frac{8,746}{30,000} - 0,626 \cdot 0,280}{0,120} = 0,970\ W/(m^2 \cdot K)$$

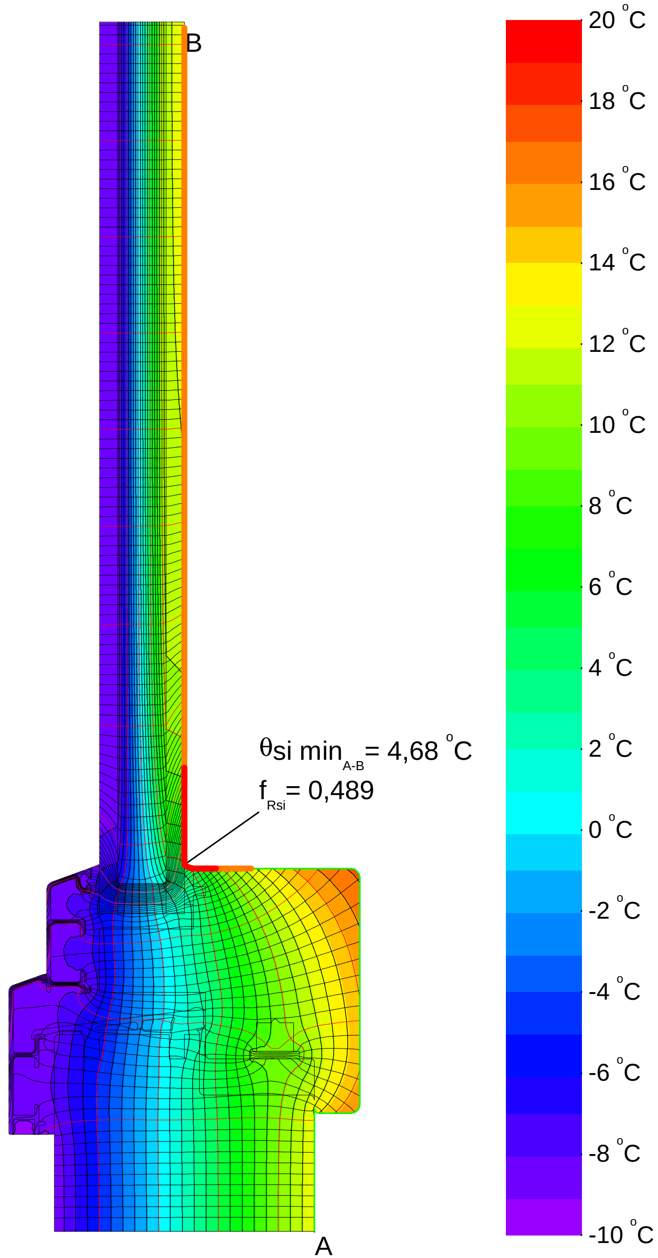
Timber-aluminum - Warm, temperate **Stainless steel spacer**

Passive House Institute

Material	λ[W/(m·K)]	ε
Aluminum I Aluminium 10456	160,000	0,900
Argon 16 mm in28 mm U 1,2	0,025	
EPDM	0,250	0,900
Glass I Glas	1,000	0,900
Polysulfid (1)	0,400	0,900
Edelstahl Abstandhalter	0,610	
Spruce Fir I Fichte, Tanne	0,110	0,900
Steel I Stahl	50,000	0,900
Unvent. cavity I unbel. Hohlr.		
slightly vent. cav. I leicht bel. Hohlr.		



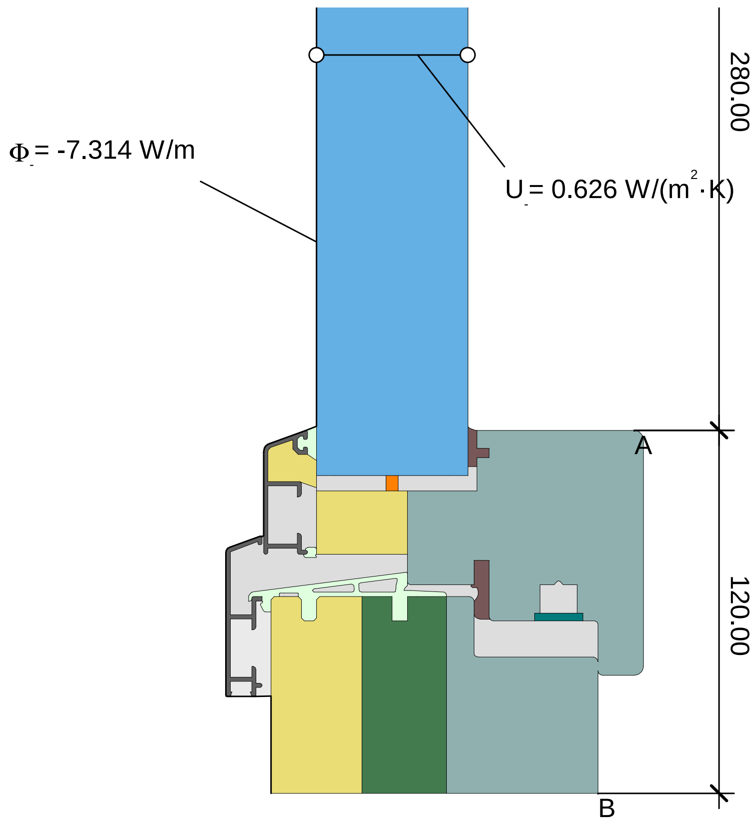


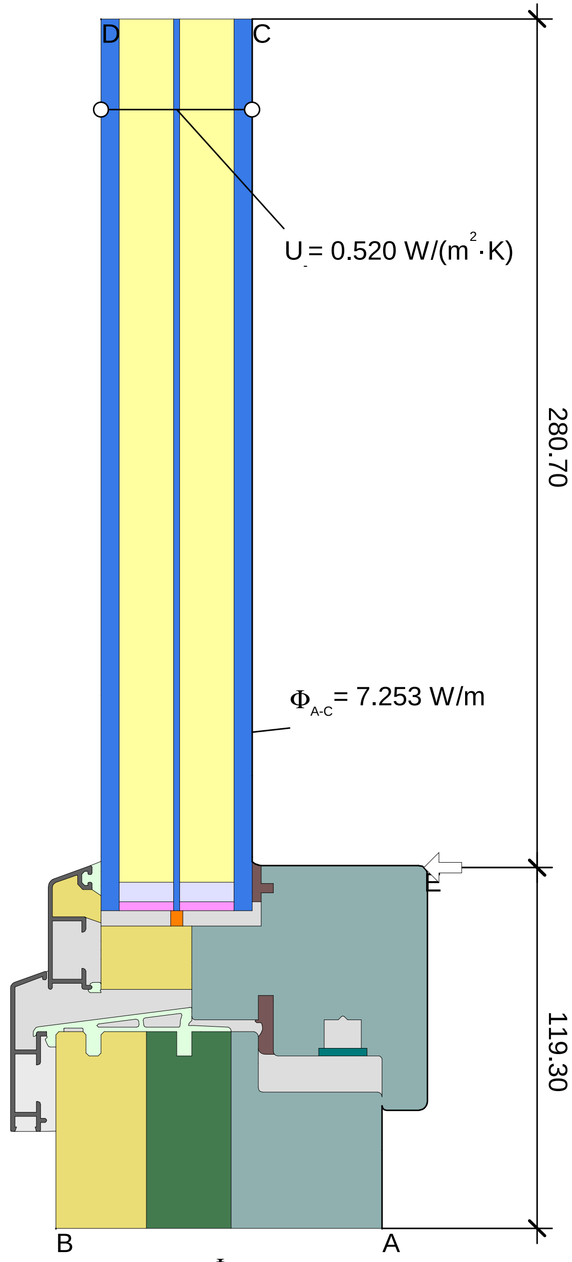


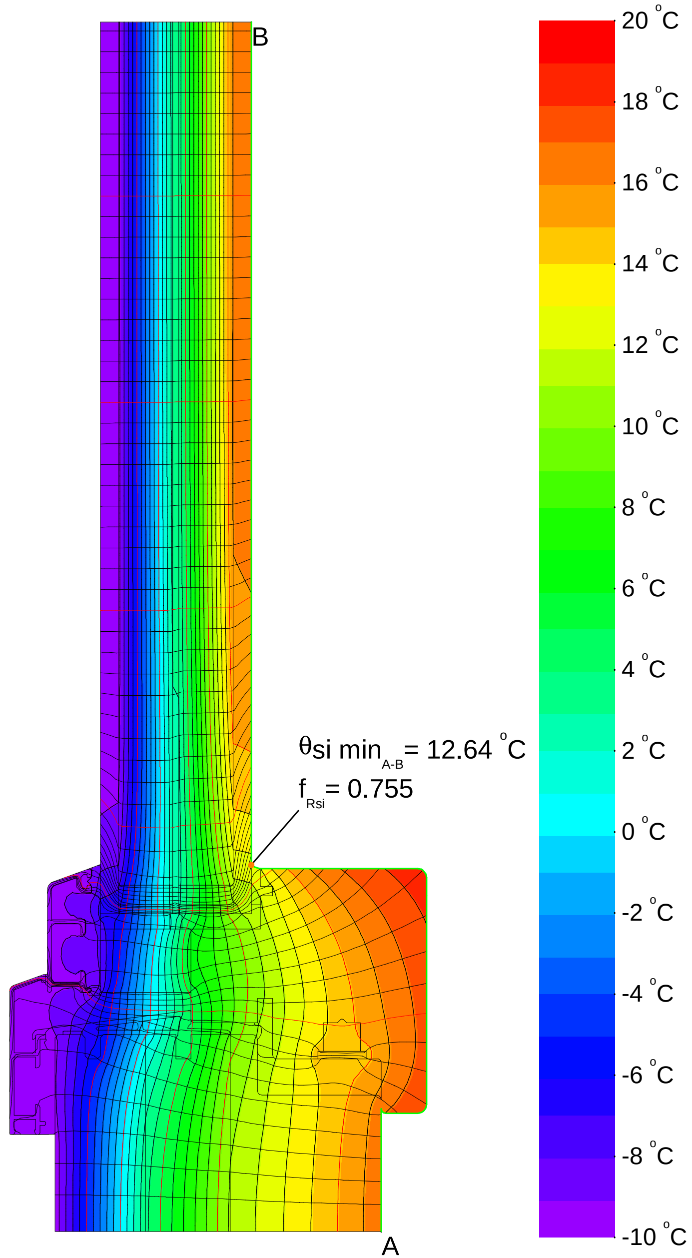
$$U_{f\,A,B} = \frac{\frac{\Phi}{\Delta T} - U_p \cdot b_p}{b_f} = \frac{\frac{12,945}{30,000} - 1,031 \cdot 0,280}{0,120} = 1,190\ W/(m^2 \cdot K)$$

$$\Psi_{A\text{-}E\text{-}C,*} = \frac{\Phi}{\Delta T} - U_1 \cdot b_1 - U_2 \cdot b_2 = \frac{16,053}{30,000} - 1,190 \cdot 0,120 - 1,200 \cdot 0,280 = 0,056\ W/(m \cdot K)$$

Material	λ[W/(m·K)]	ε
Aluminum I Aluminium 10456	160.000	0.900
Ar18 in 50 mm U 0,52	0.021	
ENERfoam	0.040	
EPDM	0.250	0.900
Glass I Glas	1.000	0.900
Insulation I Wärmedämmung 022	0.022	0.900
Insulation I Wärmedämmung 040	0.040	0.900
Polysulfid (1)	0.400	0.900
SWISSPACER Ultimate Box 2	0.140	
Soft-PVC I Weich-PVC	0.140	0.900
Spruce Fir I Fichte, Tanne	0.110	0.900
Steel I Stahl	50.000	0.900
Unvent. cavity I unbel. Hohlr.		
slightly vent. cav. I leicht bel. Hohlr.		



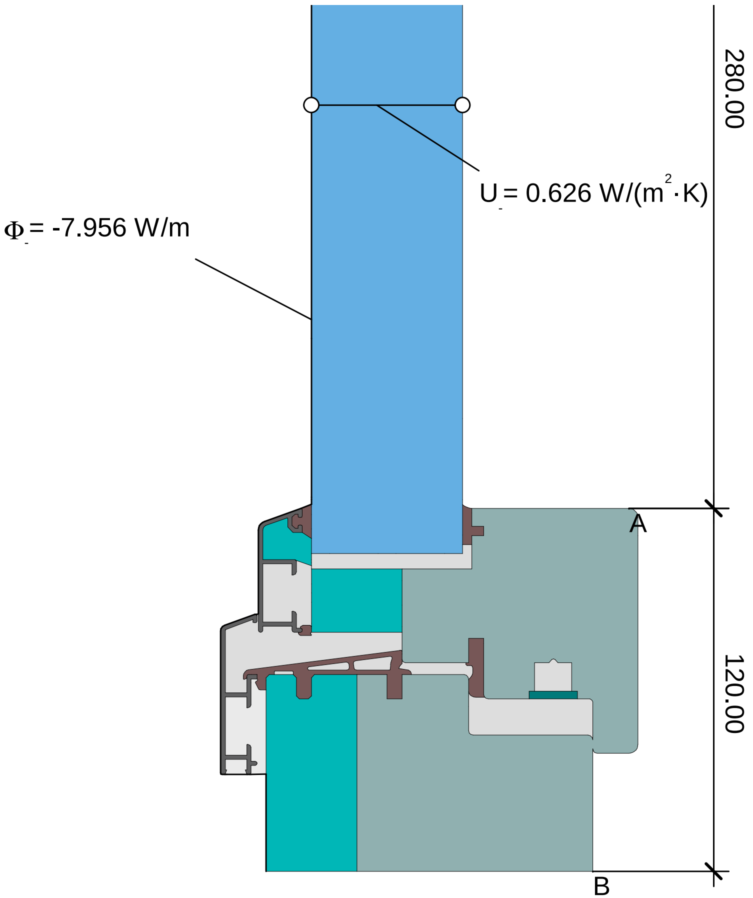


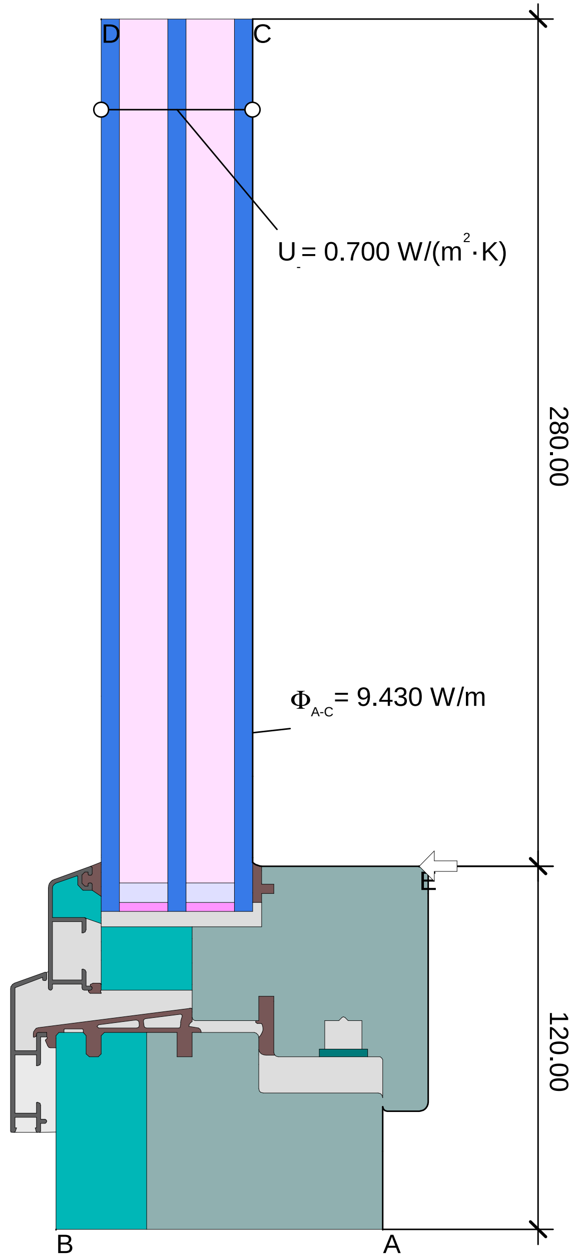


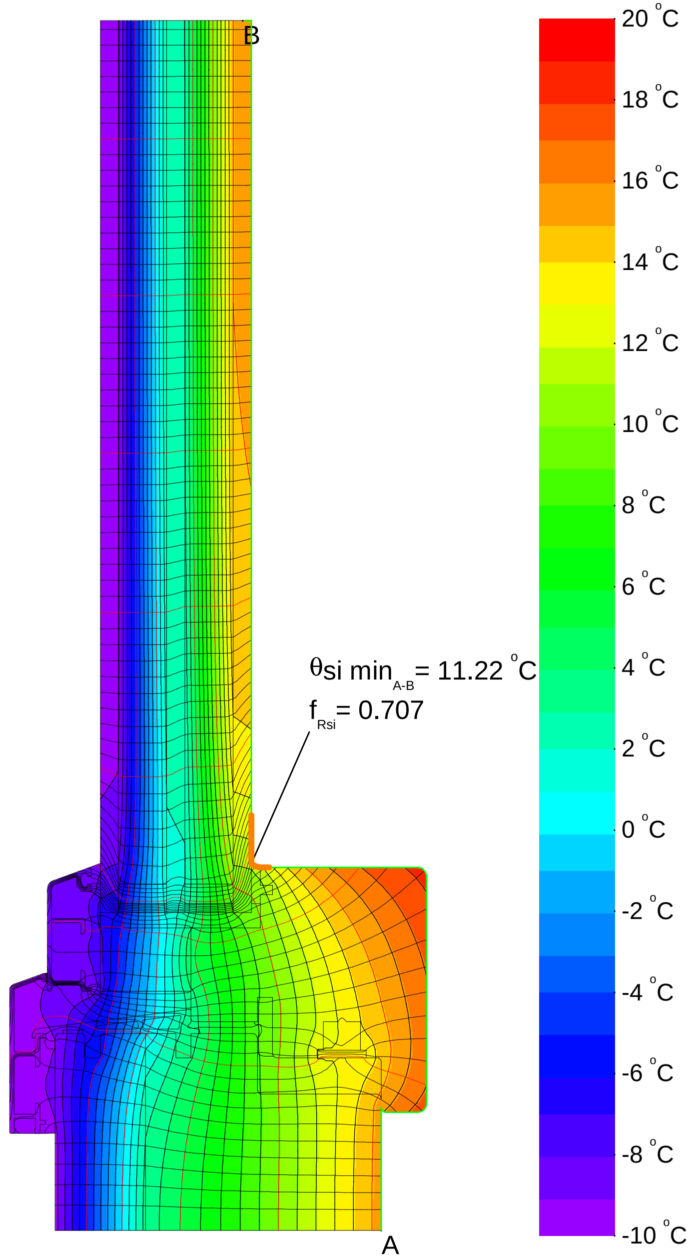
$$\Psi_{A\text{-}E\text{-}C,*} = \frac{\Phi}{\Delta T} - U_1 \cdot b_1 - U_2 \cdot b_2 = \frac{7.253}{30.000} - 0.572\cdot 0.119 - 0.520\cdot 0.281 = 0.028\ \mathrm{W/(m\cdot K)}$$

$$U_{f\,A,B} = \frac{\frac{\Phi}{\Delta T} - U_p \cdot b_p}{b_f} = \frac{\frac{7.314}{30.000} - 0.626\cdot 0.280}{0.120} = 0.572\ \mathrm{W/(m^2\cdot K)}$$

Material	λ[W/(m·K)]	ε
Aluminum I Aluminium 10456	160.000	0.900
Argon 16 mm in 50 mm U 0,7	0.026	
EPDM	0.250	0.900
Glass I Glas	1.000	0.900
Insulation I Wärmedämmung 035	0.035	0.900
Polysulfid (1)	0.400	0.900
SWISSPACER Ultimate Box 2	0.140	
Spruce Fir I Fichte, Tanne	0.110	0.900
Steel I Stahl	50.000	0.900
Unvent. cavity I unbel. Hohlr.		
slightly vent. cav. I leicht bel. Hohlr.		



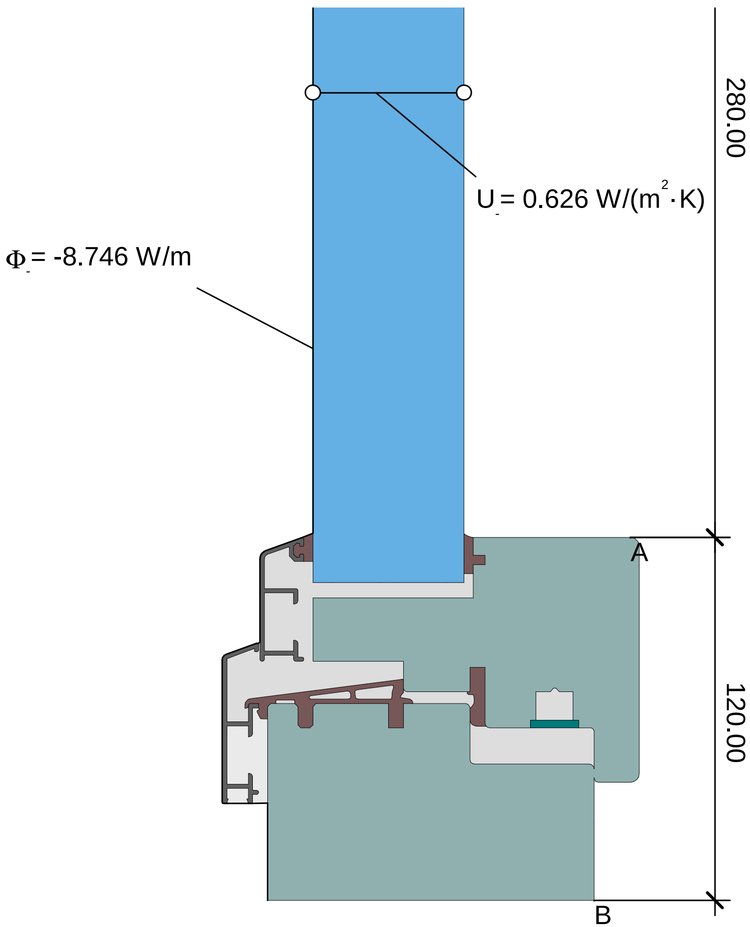


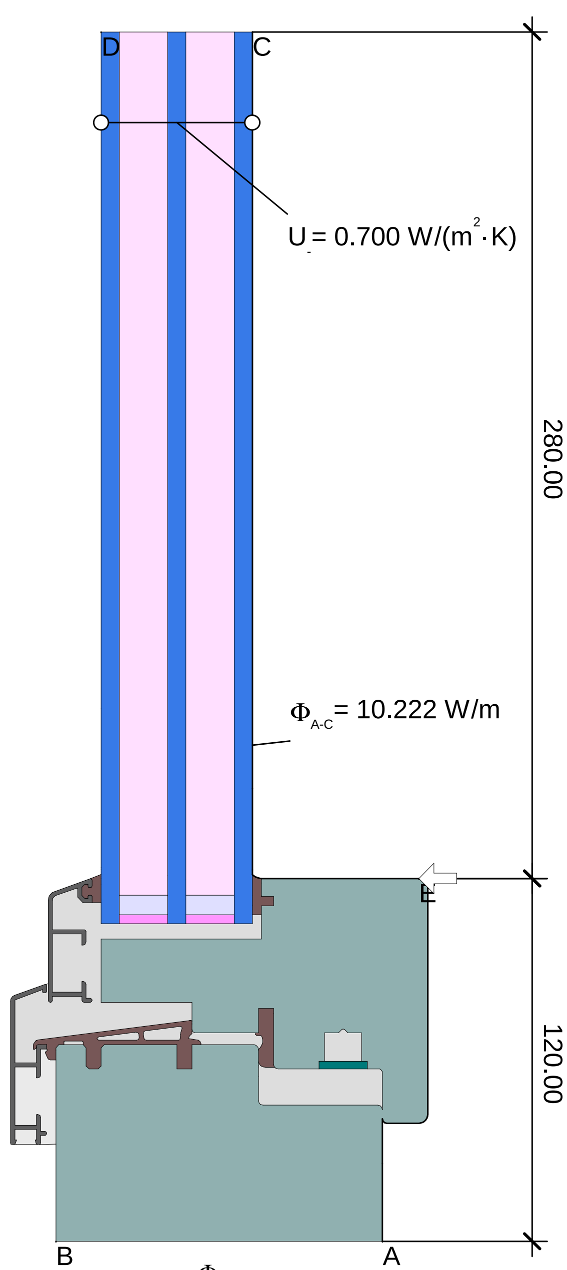


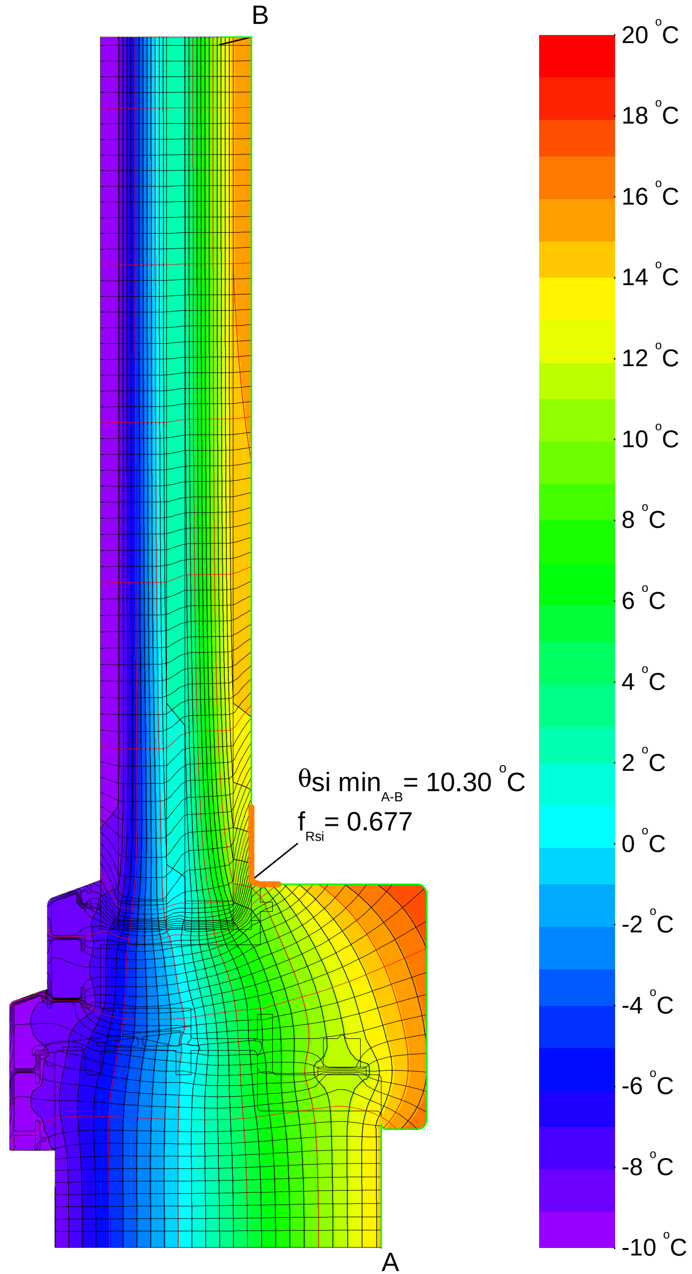
$$U_{f\,A,B} = \frac{\frac{\Phi}{\Delta T} - U_p \cdot b_p}{b_f} = \frac{\frac{7.956}{30.000} - 0.626\cdot 0.280}{0.120} = 0.750\ \mathrm{W/(m^2\cdot K)}$$

$$\Psi_{A\text{-}E\text{-}C,*} = \frac{\Phi}{\Delta T} - U_1\cdot b_1 - U_2\cdot b_2 = \frac{9.430}{30.000} - 0.750\cdot 0.120 - 0.700\cdot 0.280 = 0.028\ \mathrm{W/(m\cdot K)}$$

Material	λ[W/(m·K)]	ε
Aluminum I Aluminium 10456	160.000	0.900
Argon 16 mm in 50 mm U 0,7	0.026	
EPDM	0.250	0.900
Glass I Glas	1.000	0.900
Polysulfid (1)	0.400	0.900
SWISSPACER Ultimate Box 2	0.140	
Spruce Fir I Fichte, Tanne	0.110	0.900
Steel I Stahl	50.000	0.900
Unvent. cavity I unbel. Hohlr.		
slightly vent. cav. I leicht bel. Hohlr.		







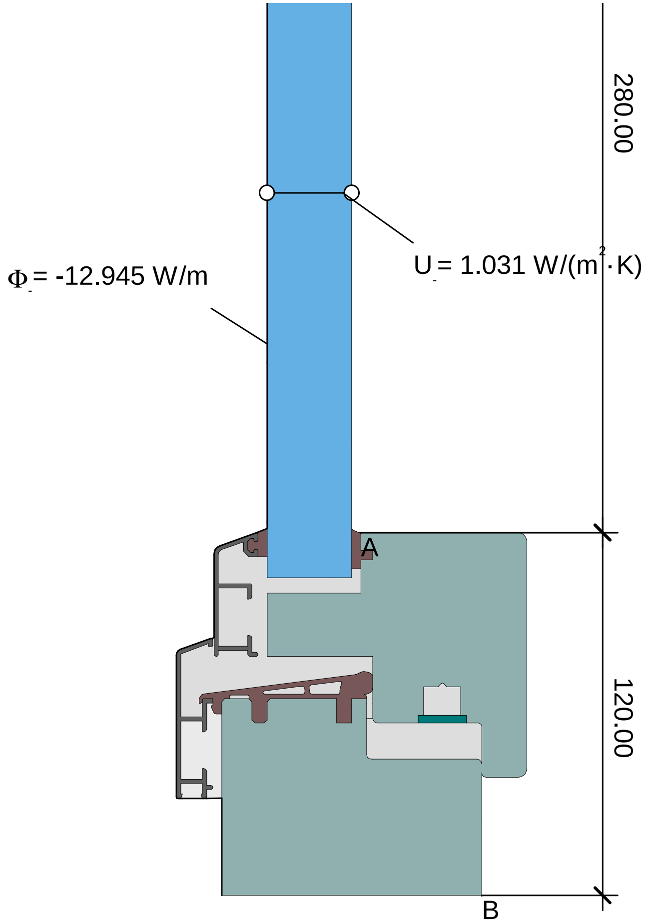
$$\psi_{A\text{-}E\text{-}C,*} = \frac{\Phi}{\Delta T} - U_1 \cdot b_1 - U_2 \cdot b_2 = \frac{10.222}{30.000} - 0.970 \cdot 0.120 - 0.700 \cdot 0.280 = 0.028 \text{ W/(m·K)}$$

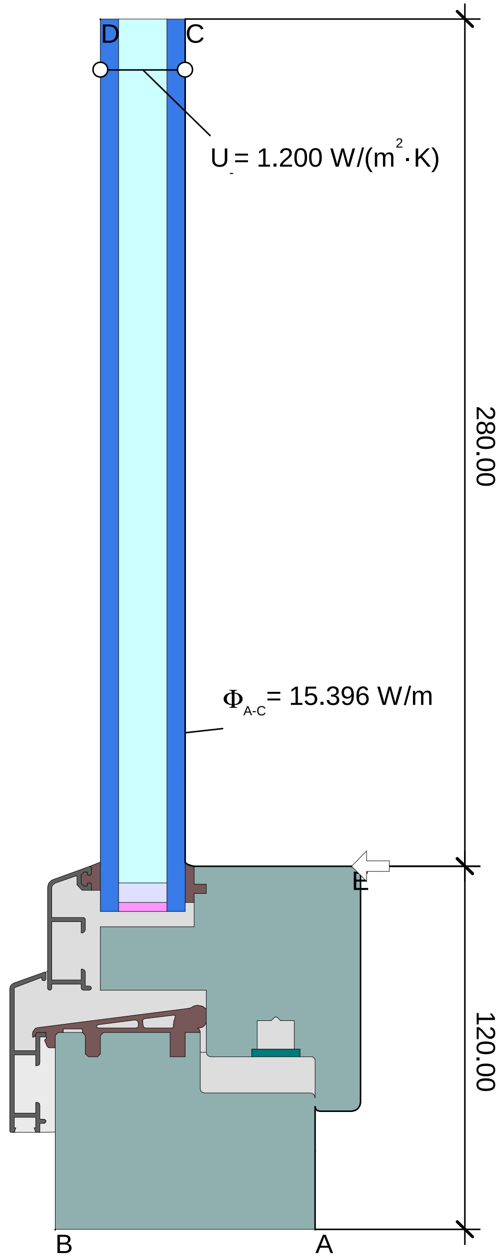
$$U_{f\,A,B} = \frac{\frac{\Phi}{\Delta T} - U_p \cdot b_p}{b_f} = \frac{\frac{8.746}{30.000} - 0.626 \cdot 0.280}{0.120} = 0.970 \text{ W/(m}^2\text{·K)}$$

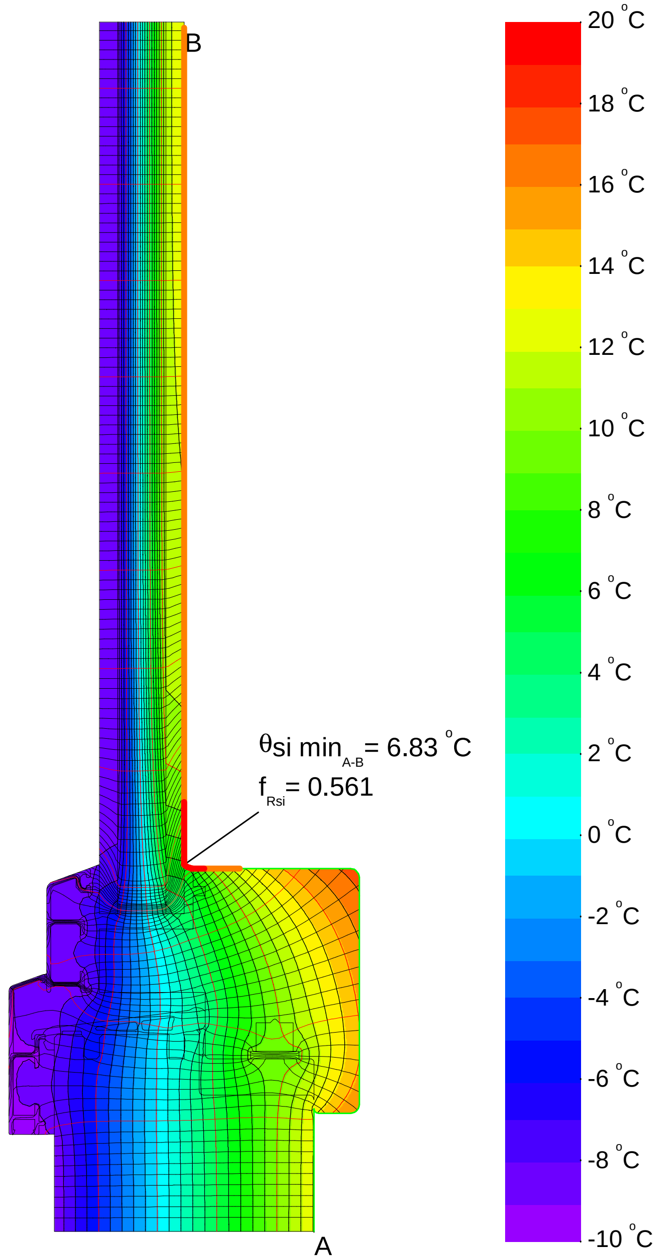
Timber-aluminum - Warm, temperate **SWISSPACER** **SWISSPACER Ultimate** **0707sp01**

Passive House Institute

Material	λ[W/(m·K)]	ε
Aluminum I Aluminium 10456	160.000	0.900
Argon 16 mm in28 mm U 1,2	0.025	
EPDM	0.250	0.900
Glass I Glas	1.000	0.900
Polysulfid (1)	0.400	0.900
SWISSPACER Ultimate Box 2	0.140	
Spruce Fir I Fichte, Tanne	0.110	0.900
Steel I Stahl	50.000	0.900
Unvent. cavity I unbel. Hohlr.		
slightly vent. cav. I leicht bel. Hohlr.		







$$U_{f\,A,B} = \frac{\frac{\Phi}{\Delta T} - U_p \cdot b_p}{b_f} = \frac{\frac{12.945}{30.000} - 1.031 \cdot 0.280}{0.120} = 1.190\ \mathrm{W/(m^2 \cdot K)}$$

$$\psi_{A\text{-}E\text{-}C,*} = \frac{\Phi}{\Delta T} - U_1 \cdot b_1 - U_2 \cdot b_2 = \frac{15.396}{30.000} - 1.190 \cdot 0.120 - 1.200 \cdot 0.280 = 0.034\ \mathrm{W/(m \cdot K)}$$