Passive cooling and heating using adaptable insulation

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Abstract

The insulation of opaque building envelopes has significantly increased in the last decades, mainly with the aim to lower the energy need for heating and cooling. Although appropriate in most situations, a thermal separation between the in- and outside environment on the other hand impedes possible beneficial energy flows pertaining to e.g. passive solar gain in winter and passive cooling in summer. Therefore, the energy performance of an envelope could be further optimized by adapting its insulation value depending on circumstances. Adaptable insulation (AI) is especially interesting for large uninterrupted surfaces such as the ground floor and roof. AI in the ground floor allows the passive utilization of the thermally massive soil for cooling. For roofs the solar gain during daytime in winter can be utilized, and the convective/radiate cooling to the air/sky during nighttime in summer.

In this paper, possible advantages of AI with respect to energy saving are examined based on theoretical considerations and dynamic numerical simulations. A sensitivity analysis will be performed with respect to influencing factors such as thermal properties of the envelope, internal heat load, building thermal mass etc. Since the number of parameters involved is large, physical quantities are lumped in characteristic parameters. Graphic design guidelines are presented.

Keywords

Adaptable insulation, gas-filled panel, insulation, passive cooling, passive energy, buildings.

Total number of words: 4000

1 Introduction

A well-insulated building envelope is nearly always desired from the point of view of energy demand (Keller, 2005) and indoor comfort. In a hot and sunny climate, transmission of solar heat through the building shell should be avoided in order to maintain a comfortable indoor temperature in non-conditioned rooms or to save cooling energy, while in a cold climate heat transmission to the outside must be avoided to save heating energy. Both arguments certainly hold for static conditions. However, mainly due to daily variations in the weather, periods exist during which good insulation is *not* desired. For example, on a sunny winter day, the outside surface temperature of an irradiated envelope may be higher than the inside temperature. A non-insulated building skin would allow the transmission of passive solar energy, lowering the energy demand for heating. In addition, during the cooler nighttime in summer, excess heat may be discharged by transmission through a non-insulated roof. Therefore, a lower energy demand and better thermal indoor comfort can be reached by adapting the envelope insulation depending on indoor and outdoor conditions. Besides, adaptable insulation in the ground floor would allow the passive utilization of the thermally massive soil beneath.

Adaptable insulation (AI) may be technically realized using gas-filled panels (GFP). GFPs have been developed at Lawrence Berkeley National Laboratory (Griffith et al., 1995), USA. It is essentially a hermetic plastic bag with several thin polymer aluminized films in a bonded honeycomb cellular structure inside. The thermal conductivity depends on the gas fill, which in case of air corresponds well to traditional insulation materials (0.031 W m^{-1} K^{-1}). When evacuated, its small thickness results in almost no thermal resistance. In principle it can be inflated and evacuated through a nozzle. Such a GFP is being used as thermal packaging to ship perishable cargo (Cargo Technology Inc.). Although inflatable prototypes have not been fabricated for other applications, their potential use as insulating material in building construction remains.

Another technical solution might be switchable vacuum insulation panels (s-VIP). s-VIPs have been developed and tested at the Bayerischen Zentrum für Angewandte

Energieforschung e.V. (ZAE Bayern), Würzburg, Germany. It consist of a evacuated porous plate (e.g. fumed silica) inside a barrier foil with a thermal conductivity as low as 0.004 W m^{-1} K^{-1}. The gas pressure inside may be increased by heating an incorporated hydrogen getter, yielding a factor 40 higher thermal conductance. This requires however about 5 W m^{-2} electrical energy. An application of s-VIS in a Tombe wall for solar heating is being studied at ZAE (http://www.zae-bayern.de/a2/pdf/swd_us.pdf). Only prototypes have been fabricated so far.

In this paper, the feasibility of GFP adaptable insulation is explored with the emphasis on indicative theoretical considerations with regard to its effect on energy use and thermal comfort depending on building characteristics, orientation, climate, physical properties of the soil and control strategies. Significant assessment criteria concern the heating and cooling energy saving potential of adaptable insulation, and the improvement of indoor thermal comfort in non-conditioned rooms.

2 Model calculations

To obtain insight in the energy saving potential and/or indoor thermal comfort improvement of adaptable insulation, exploratory calculations were performed for an idealized room and moderate Dutch climate with cool summers and mild winters. Reference characteristics of the room are: no windows, floor surface area 25 m^2, wall height 2.5 m, flat roof, ventilation rate 1 h^{-1}, no heat recovery. The roof consists from inside to outside of 1 cm gypsum plate, 10 cm adaptable insulation, and 10 cm concrete. The thermally active part of the inner walls and floor consist of concrete, assuming no heat flux at 10 cm depth. The internal heat load is constant 10 W m^{-2}. Weather data of 1961 was used, see Table 1. The first calculations were done for a room with heating only.

Key physical quantities describing the performance of adaptable insulation concern the heat resistance in the insulating and conducting state. Assuming a heat conduction coefficient of

0.031 W m^{-1} K^{-1} in the insulating state, a GFP of 10 cm thickness provides a heat resistance of about 3 m^2 K W^{-1}. In the evacuated conducting state the heat resistance depends on the geometry. If a 10 cm air cavity fills up the free space, a heat resistance of about 0.17 m^2 K W^{-1} remains. On the other hand, in case the gypsum plate moves along with the GFP, no air cavity is left behind and accordingly no heat-flow resistance. Both the heat resistance in the insulating and conducting state are used throughout the paper, designated by R_{ins} and R_{con}, respectively. Generally, a conducting heat resistance of 0.17 m^2 K W^{-1} is used in the calculations.

The dynamic simulation model basically consists of a set of ordinary first-order differential equations each describing the energy balance for a finite volume, or node, that represents some part of the room or structure (Clarke, 2001). For example, the roof was discretised into 4 nodes at the interfaces between inside air, gypsum plate, adaptable insulation, concrete, and outside air. The walls and floor were similarly discretised using a couple of nodes. For simplicity, inside and outside surface heat transfer coefficients were constant 2.7 and 20 W m^{-2} K^{-1}, respectively, and a roof surface solar absorption coefficient of 0.9 was assumed. The set of differential equation was set up and solved in Matlab/Simulink.

In the example of the idealized room, in fact two installations have to be controlled: the heating and the adaptable insulation. When the operative temperature T_{oper} drops below 20 ^oC convective heating is turned on, proportionally controlled by the difference between actual and set-point minimum temperature. The adaptable insulation on the other hand, is governed by two parameters: T_{oper} and the heat flow direction (i.e. temperature difference) over the insulation. The control for the AI is as follows:

In the conducting state if

- T_{oper} < 20 ^oC and the heat flow is towards the room.
- T_{oper} > 21 ^oC and the heat flow is out off the room.

In the insulating state if

- T_{oper} < 20 ^oC and the heat flow is out of the room.

- T_{oper} > 21 °C and the heat flow is towards the room.

If 20 °C < T_{oper} < 21 °C, the AI remains in its previous state.

3 Results

Figure 1 shows the simulated indoor temperature for two situations. One with static insulation in the roof (R_{ins} = R_{con} = 3 m^2 K W^{-1}) and the other with adaptable insulation ($R_{AI,ins}$ = 3 m^2 K W^{-1}). It is assumed that an air-filled cavity is left behind when the adaptable insulation is evacuated, leaving an effective 'conductive' resistance $R_{AI,con}$ = 0.17 m^2 K W^{-1}. It is clearly seen that with static insulation, the indoor temperatures from May till October are generally about 5 degrees higher than with adaptable insulation. A more comfortable indoor climate therefore results in summertime. The cooling effect of AI corresponds to a sensible cooling power of about 4 W per m^2 surface area and a total free cooling energy of 50 MJ y^{-1} m^{-2}. In case the effective 'conductive' resistance is nearly zero (instead of 0.17 m^2 K W^{-1}), the free cooling energy is 8% higher.

3.1 Energy demand

Besides thermal comfort, another quantitative performance indicator for AI is obtained by considering a room with both heating and cooling. The energy demand for heating and cooling in comparison with the reference demand without AI is then of particular interest. The same room is therefore modeled with cooling. Convective cooling is turned on if the temperature T_{oper} rises above 21 °C, proportionally controlled by the difference between actual and set-point maximum temperature. The control for the AI remains unaltered. For simplicity the conversion to primary energy use or costs is disregarded in the analysis.

Since the energy demand depends much on the internal heat load, the latter has been varied in the calculations to obtain some more insight. Results for the cooling, heating and total demand are shown in the upper two plots in Figure 2 for the reference case with static insulation (left) and with adaptable insulation (right). In the lower-left and lower-right graph of this figure, the energy savings due to AI is presented. It shows that at low internal heat loads, when only heating is necessary for this room, the absolute saving is fairly constant 40 – 50 MJ m^{-2}, corresponding to a relative saving of 18 %. At internal heat loads > 7 W m^{-2}, when cooling becomes dominant, higher relative savings are observed. For 10 < Q_{int} < 20 W m^{-2} a rather constant value of 75 % is calculated, corresponding to an absolute saving between 50 and 200 MJ m^{-2}. In this range, the contribution of the original cooling demand varies from 40 % to nearly 100 %. For Q_{int} > 20 W m^{-2} the relative savings starts to decrease. It appears that this offset is marked by the point at which the original energy demand becomes dominated by cooling. At very high internal heat loads, the relative savings even decrease to a theoretical asymptotic value of 0 %. This has to do with the fact that the absolute saving has an asymptotic maximum (approx. 600 MJ m^{-2}), reached in this particular case at an internal load of 60 W m^{-2} (not visible in the lower-left plot of Figure 2). The free cooling upper limit is a result of the minimum heat resistance of the roof in its conducting state.

The results illustrate that AI is of particular interest for buildings with a relatively high cooling load. It is furthermore important to have a climate with moderate temperatures. A climate with continuous high outdoor temperatures (also during the night) wouldn't allow the discharge of heat by transmission through the building envelope. A climate with continuous low outdoor temperatures isn't favorable as well because insulation is required most of the time. In the following, the discussion is therefore limited to buildings with a relatively high cooling load, a moderate climate that allows free cooling, and to the effect of AI on the cooling demand.

3.2 Influence parameters

Ventilation

So far, a constant ventilation rate of 1 h^{-1} has been assumed. Such a low value may be found in dwellings, but in offices and public buildings usual ventilation rates are about 2 h^{-1} - 4 h^{-1} or higher depending on the degree of occupation. Results of calculations with a ventilation rate of 2 h^{-1} and 4 h^{-1} are shown in Figure 3 and 4. Although these figures present data for cooling and heating, the discussion will be limited to cooling only. The heating demand is after all not very meaningful because it lacks the influence of ventilation heat recovery. From the results in Figures 3 and 4 it can be concluded that, below the free cooling limit of AI,

- Both the absolute and relative energy savings due to AI decrease with increasing ventilation.
- When cooling dominates (Q_{int} > 20 W m^{-2}) , the absolute effect of AI is inversely proportional to the amount of ventilation.

Thus, free cooling by ventilation and by transmission give similar results, which of course is not a very surprising result as both processes are mainly driven by the same potential: the temperature difference between in- and outdoor.

Variable internal heat load

Another simplification concerned a constant internal heat production. In practice, the amount of heat released inside depends strongly on time due to occupancy, use of equipment, solar access etc. To get a first impression of the effect of this variability, simulations were done with an idealized time-schedule for the heat load: a constant production rate between 6 h and 18 h, and no production between 18 h and 6 h. Results are shown in Figure 5 as a function of the *mean* heat production rate for a ventilation rate of 2 h^{-1}. In comparison with Figure 3, it is seen that until a mean production of about 10 W m^{-2} both results are not so different because the demand is dominated by heating: the AI is in the insulating state most of the time. Above this value, the effectiveness of AI decreases due to the variability.

Solar absorption at external roof surface

Although absorption of solar radiation at the roof surface certainly affects the cooling need, it appears that the saving due to AI is not so sensitive to it. Apparently, most transmission free cooling is obtained during the night.

Room thermal mass

Although the room thermal mass influences the energy need for heating and cooling, (especially for a variable heat load), the saving due to AI is hardly affected by the building mass. At a variable 10 W m^{-2} heat load the absolute saving of 20 MJ m^{-2} is rather constant, while at a variable 20 W m^{-2} load the relative saving for cooling is constant 40 %. These results indicates that, at first instance, the room thermal mass can be neglected in analyzing the effectiveness of AI.

Thermal mass construction

Model calculations have shown that thermal capacity of the roof layers between AI and outside hardly influences on the effectiveness of AI. Similarly, also the thermal capacity of the roof layers between AI and inside has almost no effect.

3.3 Conclusions

Based on the above calculations and sensitivity analysis, it has been demonstrated that the saving potential of AI depends on the

- total (= ventilation +transmission) heat loss of the building in both the insulating and conducting state of AI.
- room heat load.
- outside surface temperature of the adaptable construction.

but hardly depends on the

- thermal mass of the room and of the materials in the adaptable construction.

4 Modeling the Problem

For decision making in the initial stage of a design, it is important to have a have a quick and easy tool such as a graphs, tables, spreadsheet or simplified model at hand that estimate the effectiveness of adaptable insulation.

Such tools have been made for 'normal' buildings to estimate the energy demand for heating and cooling. For example, Keller et al. (2005) showed that for the dynamic thermal behavior (free-running temperature) of a room, given a climate scenario and ignoring the internal heat production, can generally be described by only two parameters: the time-constant of the room defined as

$$\frac{C}{K} \tag{0.1}$$

where C is the storage capacity (J K^{-1}) and K is the generalized loss factor (W K^{-1}) accounting for transmission and ventilation heat losses, and a solar temperature coefficient (K) defined as

$$\frac{I}{K} \tag{0.2}$$

where I is the solar heat load (W). The solar temperature coefficient describes the influence of solar access on the effect of the indoor (or outdoor) temperature. Based on this idea, the energy demand for heating can be easily optimized using design graphs given a specific climate.

This analytical approach is based on physical reasoning and may therefore be extended to other situations. However, such an approach can not be followed for AI. First, analytical methods are generally confined to relatively simple and linear mathematical descriptions. The problem at hand is non-linear because the transmission loss coefficient depends on the indoor temperature and the heat flow direction over the AI. Secondly, more than just 2 parameters play a role when AI is applied. Not only the internal heat production is important, but also the difference in heat loss that can attained by AI. Although we may disregard the room thermal mass, a lumped-parameter analytical design tool may still become too complicated for adaptable insulation.

In another model, the energy demand for heating and cooling is calculated based on the total heat gain and heat loss, a utilization factor and a room time-constant. For example, in the draft European standard prEN ISO 13790, the energy need for heating is calculated as

$$Q_{\mathrm{n,h}} = Q_{\mathrm{l,h}} - \eta_{\mathrm{h}} Q_{\mathrm{g,h}} \tag{3}$$

where $Q_{\mathrm{l,h}}$ is the total heat loss due to transmission and ventilation, $Q_{\mathrm{g,h}}$ is the solar plus internal heat gain and η_{h} is the utilization factor. Calculations may be done per season or per month. Furthermore, based on results of many numerical simulations, a regression function for the utilization factor has been derived:

$$\eta_{\mathrm{h}} = \frac{1-\gamma^{a_{\mathrm{h}}}}{1-\gamma^{a_{\mathrm{h}}+1}} \tag{4}$$

with γ the ratio of heat gains and losses:

$$\gamma = \frac{Q_{\mathrm{g,h}}}{Q_{\mathrm{g,l}}} \tag{5}$$

and a_{h} a function of the time constant *C/K*. This model may, mutatis mutandis, also be applied for calculating the cooling need.

This approach is based on a regression analysis of results of many model calculations. Unfortunately, it appeared to be unusable to apply in a situation with variable heat loss. On the other hand, the approach itself is useful to adopt. Basically, the strategy is to identify as few as possible characteristic parameters that play a role. In this way, a many-parameter problem is reduced to a simpler model from which guidelines may be derived.

As has been observed above, the following parameters need to be considered for a given climate:

- heat loss of the building in the insulating and conducting state of AI.
- room heat load

Let $H_{tot,ins}$ (W K^{-1} m^{-2}) be the total heat loss coefficient of the room per m^2 floor area with AI in the insulating state, and $H_{tot,con}$ (W K^{-1} m^{-2}) the total heat loss coefficient with AI in the conducting state. Furthermore, it is assumed that the room heat load varies with a diurnal period. Let W_0 (W m^{-2}) be the constant part, and W_1 the extra heat load (W m^{-2}) between 6 h and 18 h. The heat load contains all heat sources (internal, incoming solar). For simplicity, in this paper the influence of W_0 will however be disregarded: it is assumed that W_0 = 0 W m^{-2}. This may reflect the situation in schools and offices. So, there is only heat production between 6 h and 18 h with a value W_1.

A design tool may consist of graphs showing the energy saving potential of AI in dependence of these 3 most influencing parameters. At the left side of Figure 7 the absolute yearly cooling energy saving (MJ m^{-2}) due to AI is shown in three separate surface plots for W_1 = 20, 40 and 80 W m^{-2}. In each plot the total heat loss coefficient due to transmission and ventilation with AI in the insulating state, $H_{tot,ins}$, is set out on the ordinate, while the change in heat loss, $\Delta H = H_{tot,con} - H_{tot,ins}$, attained by changing AI into the conducting state is set out on the abscissa. At the right side of Figure 7 the same plots are shown for the relative saving. These results shows that:

- It is not worthwhile to use AI at very low heat loads. Theoretically, the transmission and ventilation losses should be as small as possible at no heat load.

- At very high loads, AI saves cooling energy but the relative contribution gets worse. Most of the heat must be taken away with active measures, or the static transmission loss should be increased to lower the cooling energy demand.
- The potential of AI is optimal both in terms of absolute and relative savings at intermediate heat loads.
- When the yearly cooling and heating energy demand are approximately balanced (H_{tot} = 1, 2 and 4 W m^{-2} K^{-1} for W_1 = 20, 40 and 80 W m^{-2}, respectively), the relative saving (up to about 50 %) seems to be linearly proportional to ΔH.

5 Conclusions

In has been shown that the energy performance of a building envelope can be further optimized by adapting its insulation value depending on circumstances. For a moderate climate as in the Netherlands, the advantage of AI mainly concerns the energy saving for cooling, and/or a better thermal indoor comfort in summer. Furthermore, by reducing the large number of parameters involved in the effectiveness of AI, a simple graphic design method could be derived to get a first indication of the energy saving potential of AI, depending on the total specific heat loss of the building and the internal heat load, given a certain climate. As yet, the time-dependency of the internal heat load was highly idealized.
In future research, more attention should be given to the usefulness of AI in other climates, more realistic heat load variations, and to other applications such as AI being the separation between indoor and a ground mass, e.g. in sheltered buildings.

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Table 1. Monthly averaged climatic data in 1961, De Bilt, The Netherlands.

	average temperature (°C)	horizontal solar irr. (MJ m^{-2})	vert. solar irr. south (MJ m^{-2})	vert. solar irr. north (MJ m^{-2})
January	2.0	80	171	33
February	6.3	138	212	53
March	7.1	267	309	97
April	10.5	380	307	130
May	11.1	525	322	201
June	15.4	578	320	212
July	15.6	458	269	187
August	16.0	403	286	155
September	16.6	294	284	108
October	11.4	200	282	75
November	4.7	84	147	36
December	1.6	62	162	25

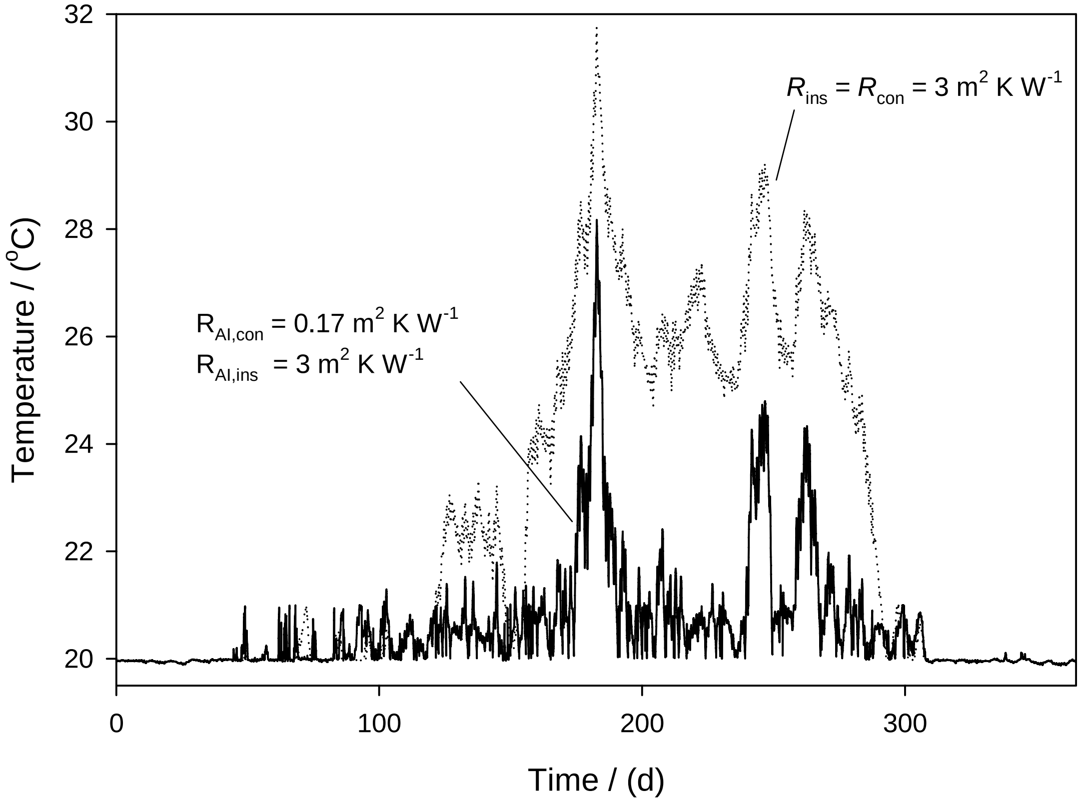

Figure 1: Indoor operative temperature as a function of time for an idealized room with static insulation (R_{ins} = R_{con} = 3 m^2 K W^{-1}) and adaptable insulation ($R_{AI,ins}$ = 3 m^2 K W^{-1}; $R_{AI,con}$ = 0.17 m^2 K W^{-1}) in the roof.

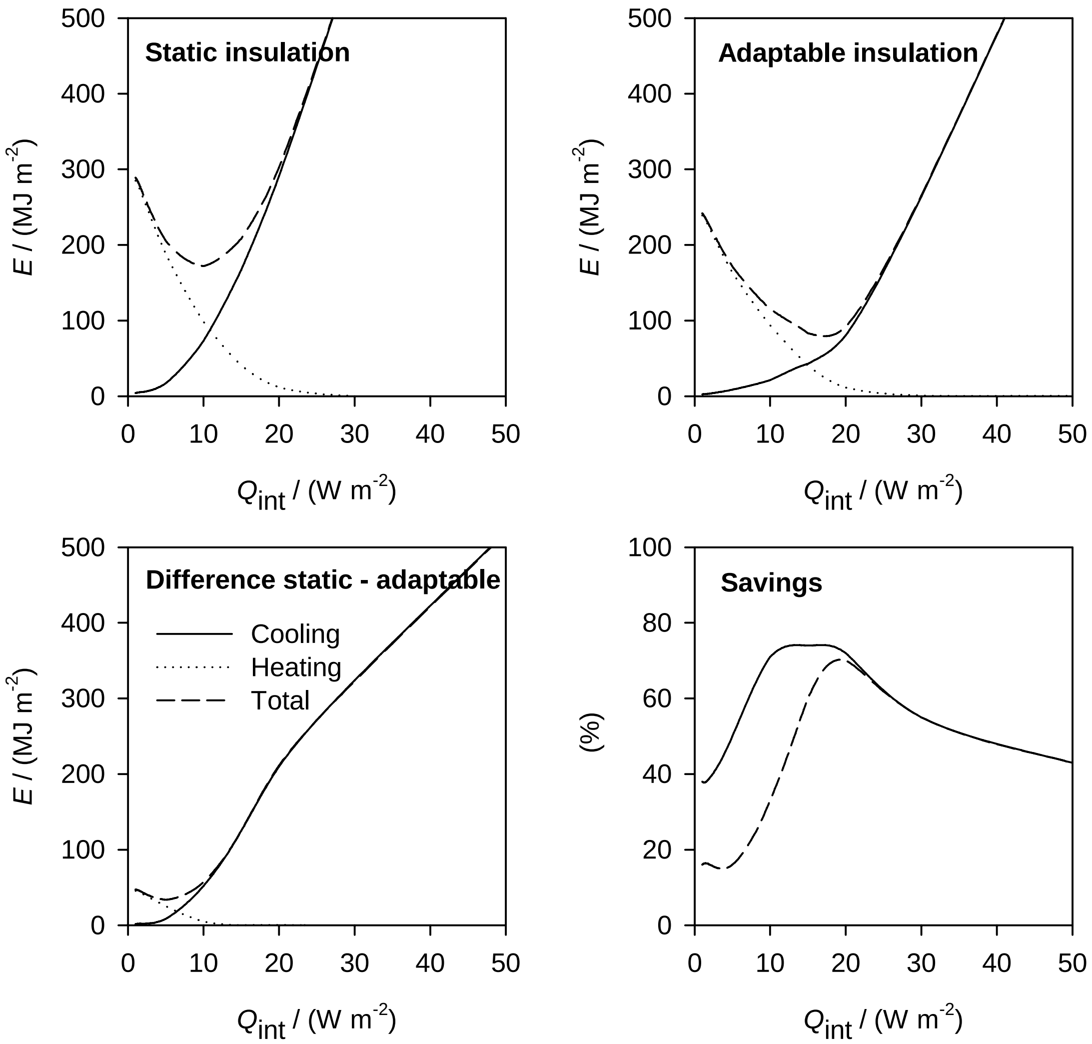

Figure 2: Annual energy demand (MJ m^{-2}) for cooling (—), heating (····) and total (---) as a function of the internal heat load for the idealized room with static insulation (upper-left), adaptable insulation (upper right) and the difference between these (lower-left). Lower-right: Energy savings due to AI as percentage for cooling (—) and total (---). Results for a ventilation rate of 1 h^{-1}.

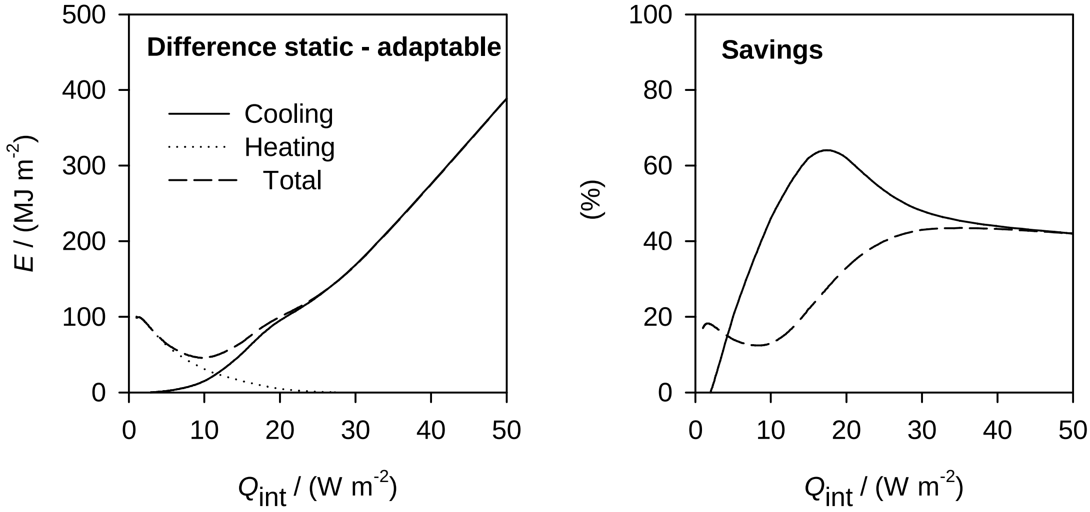

Figure 3: Results for a ventilation rate of 2 h^{-1}. Left: Energy savings due to adaptable insulation for cooling (—), heating (····) and total (---). Right: Energy savings as percentage for cooling (—) and total (---). See also Figure 2.

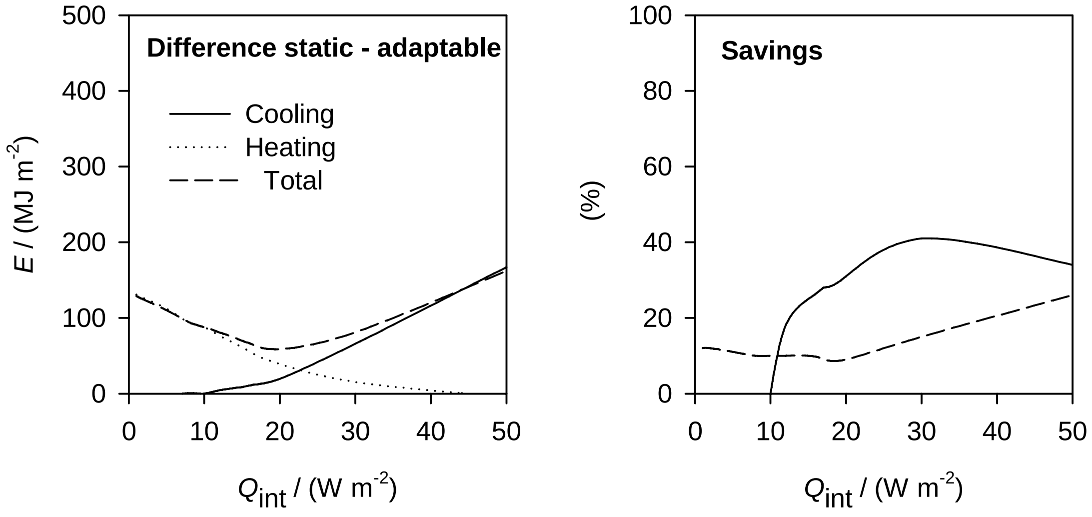

Figure 4: Results for a ventilation rate of 4 h^{-1}. See also Figure 3.

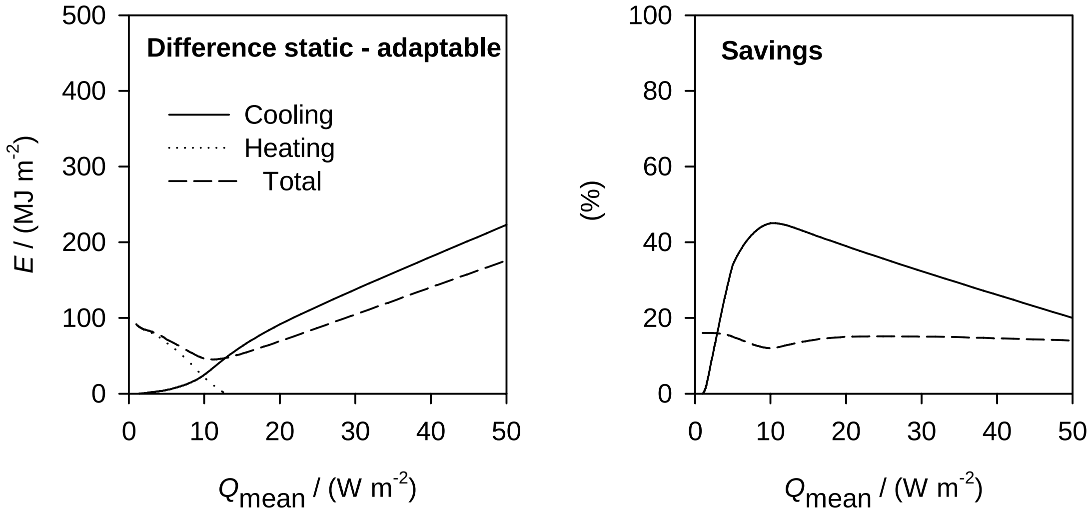

Figure 5: Results for variable internal heat production. Ventilation rate 2 h^{-1}. See also Figure 3.

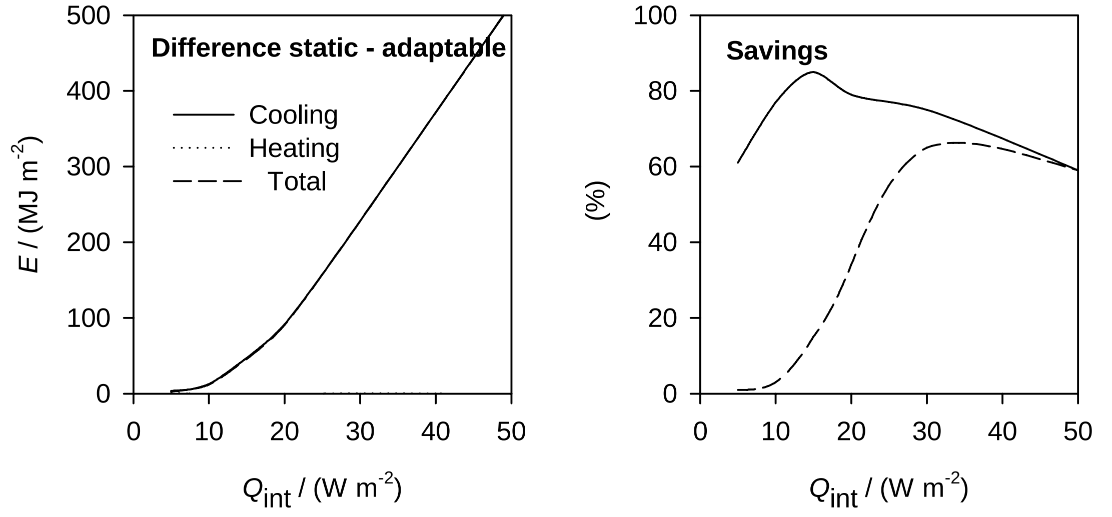

Figure 6: Results for a roof without solar absorption. Ventilation rate 2 h^{-1}. See also Figure 3.

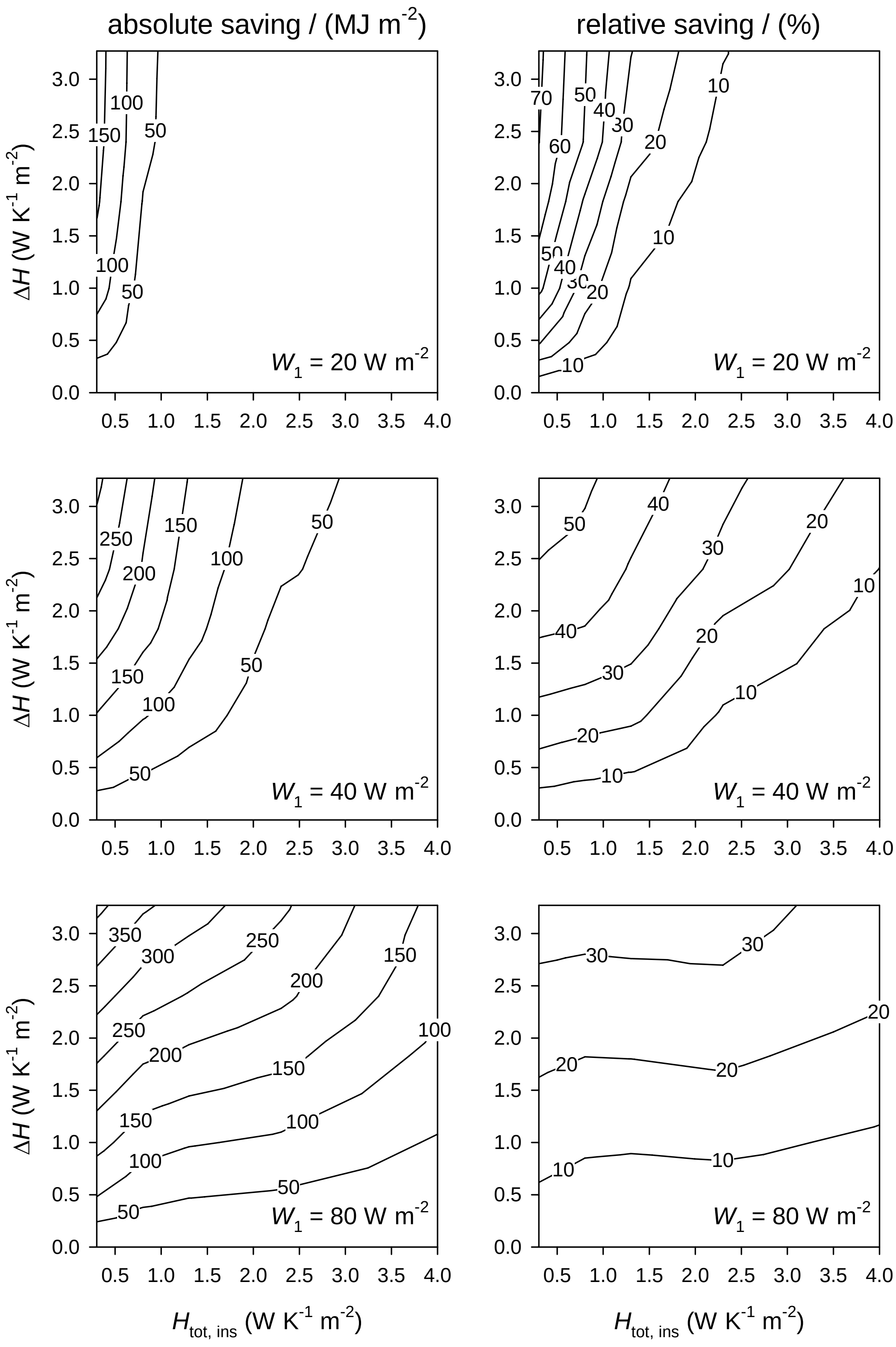

Figure 7: Surface plots of the estimated yearly absolute (left graphs) and relative (right plots) cooling energy saving due to AI for a Dutch climate as a function of the total specific heat loss coefficient with AI in the insulating state, $H_{tot,ins}$, and the change in heat loss attained by AI, ΔH. Isolines are somewhat irregular due to limited number of datapoints.