POTENTIAL ENERGY SAVING VIA DYNAMIC SHADING WITH ELECTROCHROMIC ELEMENTS IN ETFE WINDOWS

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ABSTRACT

In this article we report on our investigations on the impact of dynamic shading, integrated into ETFE fenestration elements, on the energy demand of buildings, via numerical simulation. The numerical investigations are carried out with the dynamic building simulation suite TRNSYS. The dynamic shading mechanism is based on electrochromic elements. The modelling of the electrochromic dynamic shading mechanism is based on data from commercial as well as newly developed elements. We explore the general potential for the reduction in overall energy demand in relation to various switching algorithms. The influence of the switching algorithm is explored by employing the optimization tool GenOpt.

INTRODUCTION

The use of ETFE in architectural context for fenestration, facade or roof elements is gaining greatly in popularity. Apart from its advantages in aesthetics and weight, ETFE also bears some shortcomings in terms of its thermophysical properties concerning heat retention, in comparison to regular insulation glazing units (IGU). In various preceding research projects our Institution has spent reasonable effort on the investigation and improvement of the thermo physical properties of ETFE elements for the building envelope. In the past different approaches, like for example angle of incident dependent selective shading (Cremers & Marx 2017) and low emissivity coatings (Follow-e2) have been tackled. Other concepts like pneumatic operated position switching of inversely complementary printed layers have been investigated by others (Flor et al. 2018). In this work we address the impact of dynamic shading by means of electrochromic elements on the energy demand of a building in the context of ETFE membrane architecture.

The reported investigations are conducted by means of numerical simulations, employing the dynamic building simulation program TRNSYS. It seems noteworthy to point out that the thermophysical processes within an ETFE cushion, with regard to heat transfer, differ somewhat to the relevant processes within regular IGUs. Some thermo physical effectsregarding the heat transfer through the cushion and the proper modelling of them will therefore be discussed in our work. The article is structured as follows:

In the first section, “HEAT TRANSFER IN ETFE CUSHION”, we address the fundamental thermo physical phenomena with regard to fenestration elements in general and tackle the peculiarities of heat transfer processes within pneumatic ETFE elements, as well as their proper numerical modelling.

In the subsequent section, “NUMERICAL SIMULATION” we introduce the numerical tools and models utilized for the investigations.

In section “RESULTS AND ANALYSIS” we present the results of our investigation and discuss the impact of our findings.

Finally, in the last section, “SUMMARY AND OUTLOOK”, we present a synopsis of the conducted efforts and elaborate on future prospects.

HEAT TRANSFER IN ETFE CUSHIONS

Heat transfer processes are generally driven by the temperature gradient across a medium due to the presence of energy wells and sinks in the vicinity. In the case of transparent building elements the incident radiation and radiation transfer phenomena like reflection, absorption and transmission are of increased significance for the heat transfer processes and energy balance of a building. An overview of the spectral distribution of radiative energy of the incoming solar radiation in terms of the spectral irradiance of the AM1.5 spectrum (according to ASTM G173-03(2012)) as well as the photopic luminosity function $V_M(\lambda)$ of human vision (according to the CIE (Vos 1978)) and the spectral thermal blackbody radiation, emitted at a temperature of T = 300 K, is shown below in Figure 1.

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DOI: 10.3217/978-3-85125-786-1-42

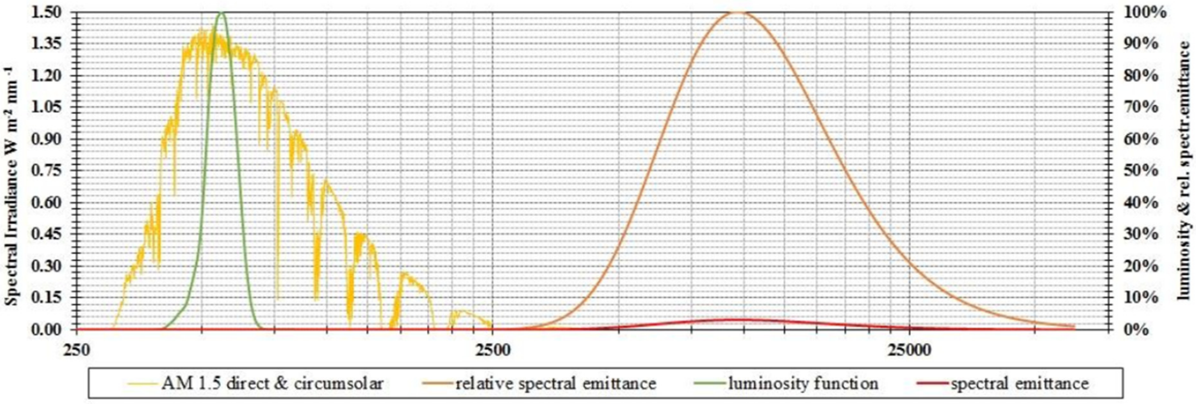

Figure 1: Spectrum of solar irradiation, luminosity function and thermal blackbody radiation.

The ratio of the overall solar radiative energy in the various spectral regions (ultraviolet UV, visual vis, infrared IR) is given below in Table 1.

Table 1:
Radiative energy ratio in specific spectral regions.

	UV 280 – 380 nm	*VIS* 380 – 780 nm	*IR* 780 – 4000 nm
Energy Fraction	2.29%	52.06%	45.65%

According to the distribution of the radiative energy to the specific spectral ranges, it should theoretically be possible to block about 48 % of the incoming radiative energy without inducing any constraints on the visual experience within the building. While conventional shading elements are typically opaque in all spectral ranges, the spectral properties of electrochromic shading elements can generally be tailored to some degree, enabling the fenestration element to retain its functionality to provide a line of sight to the outdoors to a certain degree.

The rate of energy transfer across building elements is specified by certain well-defined coefficients like the U-value for the thermal transmittance through opaque, as well as transparent elements, e.g. walls, ceilings, roofs, floors, windows and doors, and the g-value (**s**olar **h**eat **g**ain **c**oefficient - SHGC) for the overall heat transfer rate, caused by incident solar radiation including secondary heat transfer effects through transparent elements, e.g. fenestration and glass doors. The methods for the calculation and measurement of these coefficients are well-defined and documented in technical standards and regulations (e.g. DIN ISO 6946, DIN 673, DIN 410) and are well established for ordinary building elements. These Standards were designed for the characterization of building elements within a specified set of boundary conditions to provide comparability of different building elements. It is noteworthy to point out, that there are some non-negligible deviations between the calculations following different norms i.e. ISO 15099and DIN EN 673. This has already been discussed by others (Hanem et al. 2014) and will not be further elaborated on in our endeavors. In the current work we will conduct calculations according to the standards, common in the german context, i.e. DIN EN 673 and DIN EN 410, for U-value and g-value respectively.

According to the Standard DIN EN 673 the boundary conditions of the calculations are chosen in a way to comparably reproduce the heat transfer processes within a *vertical*, *plane parallel*, multi pane glazing unit, at a given temperature difference. It needs to be addressed, that the occurring physical phenomena inside an ETFE cushion element differ to a significant degree in their magnitude from the corresponding phenomena inside a regular multi pane glass window. The general thermo physical phenomena within a membrane cushion are depicted below in Figure 2.

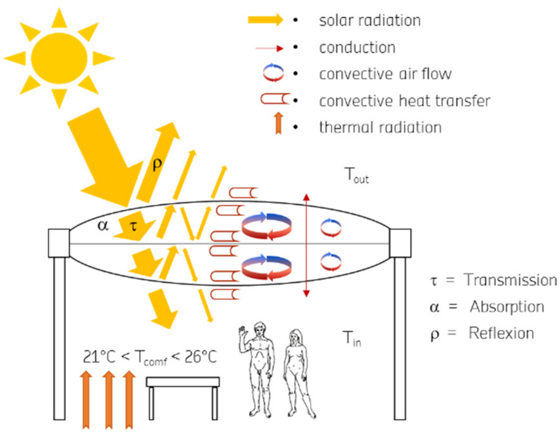

Figure 2: Heat transfer phenomena within cushion.

While the depicted general heat transfer processes, conduction, convective flow and radiation, occur likewise in ETFE-cushions and IGUs, their impact on the magnitude of the heat transfer rates differ to some degree. Especially the convective heat transfer at the inner surfaces in IGUs is considered a minor effect, due to the smallness of the interplanar gap, typically calculated with a rather simple temperature driven routine, neglecting airflow velocity within the cavity.

The manifold of deviations in the impact of the various heat transfer phenomena arise mostly from

 DOI: 10.3217/978-3-85125-786-1-42

constructional differences between membrane cushion elements and regular multi pane glazing units. Some rather obvious differences and their treatment are listed below and will be addressed in the further discussion.

The major deviations of membrane constructions from the requirements by the standards are:

- the orientation of the ETFE element. Since they are commonly applied to constitute curved building envelopes and roofs, the orientation is mostly not vertical.
- The obvious departure from plane parallelism of the boundary surfaces. Due to the flexible nature of the material the surfaces are generally not plane parallel but curved and tilted.
- The airflow within the cushion. Due to the comparably large gap between the panes, the temperature difference induces considerable air movement of streams and vortices inside the cushion with subsequent impact on the convective heat transfer processes.

Due to these differences, calculations of the U-value as well as the g-value, according to the common standards, are not entirely applicable to typical cushion constructions, since some relevant phenomena, like for example the airflow within the cushion, are typically not sufficiently taken into account by the standards. Comparability between the calculated values for ETFE cushions and IGUs is therefore not provided, strictly speaking. Due to the lack of calculation standards for irregularly shaped fenestration elements, the U-value and g-value is still mostly calculated according to the standards for regular fenestration elements. In our following remarks we try to point to resolutions to some of the shortcomings in the calculations according to the standards and give some prospects with regard to the proper numerical handling of the relevant thermo physical phenomena within ETFE cushions.

The probably most significant and most laborious to account for property seems to be the internal airflow and its influence on convective heat transfer processes on the inner surfaces. The airflow within regular fenestration elements is mostly negligible and therefore justifiably accounted for by rather simple models. These calculations are driven by the temperature difference and deal with natural convection via dimensionless parameters, i.e. the Nusselt-, Prandtl- and Grashof-Number, without taking flow velocity explicitly into account. Due to the significantly bigger gap between the boundary planes and the corresponding higher amount of air volume, air movement within cushion elements gains greatly in relevance. The phenomena of temperature driven fluid flow within ETFE cushion elements has been investigated previously by means of Computational Fluid Dynamic (CFD) calculations (Antretter 2008, Jianhui 2015). Calculations of that nature are of great value for the assessment of the impact of fluid flow within the cushion on the convective heat transfer processes for fixed thermal boundary conditions. Calculations of transient conditions are however mostly not feasible since CFD calculations are notoriously time-consuming. A straight forward coupling of dynamic building simulations and CFD calculations seems therefore prohibitive. Since a converged numerical CFD solution would have to be produced for each time step of the building simulation. Simplified procedures for the implementation of CFD solutions into transient building simulations will be addressed in future works.

The obvious difference in the geometric configuration of the surfaces, due to the generally complex curvature of the flexible material, can be tackled with the rather straight forward crude procedure of approximating the curvature as adjacent elements of different width/height, and merging the single U-values to an overall U-value.

With regard to the g-value a proper numerical treatment of the influence of the curvature on the radiative heat transfer and optical properties of a cushion would require a rigorous ray tracing calculation to handle effects like haze, scattering and diffraction properly. Investigations on the thermal and optical properties of ETFE cushions employing ray tracing routines and the coupling to dynamic building simulations have been done by others (Flor et al. 2018).

In the transfer from theoretical modelling to simulation application the degree of sophistication in the numerical models is bound to the capabilities and constraints of the simulation suite on the one hand and available computational recourses on the other hand. It is therefore mostly not realizable to implement the theoretical modelling to full extent. The identification of the relevant phenomena and their impact on the calculation is still helpful to evaluate shortcomings and the outcome of numerical simulation and take them with an additional grain of salt.

NUMERICAL SIMULATION

In this section we describe the methods, used for the numerical investigations of the influence of electrochromic shading on the energy demand of a building, in some detail. The investigations are part of the scope of the ongoing, federal funded, research project “Flex-G”, conducted in close collaboration with manufacturers and several other research institutions. The numerical work was conducted by employing a number of available computational tools and some newly created scripts for executing and controlling the simulation. The general workflow and the computational tools applied in the numerical

 DOI: 10.3217/978-3-85125-786-1-42

investigations on the topic are depicted below in Figure 3.

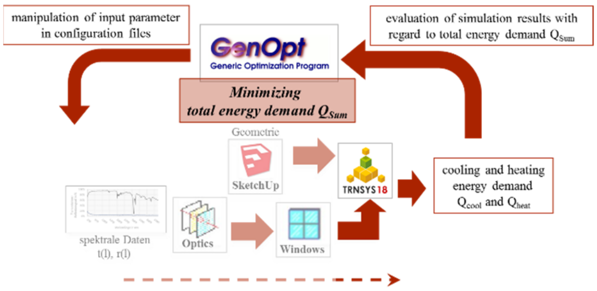

Figure 3: Workflow of the numerical simulation within optimization loop.

The dynamic building simulation was done with TRNSYS18 on the model of a generic building created with SketchUp 2017. The input data for the fenestration elements was created from spectrometric data, which was either provided by the manufacturers and collaborators, in case of the electrochromic elements, or was retrieved by spectrometric measurements at our institution, in the case of the ETFE polymer. The tool of choice, for the creation of comprehensive fenestration datasets for TRNSYS, was the free software suite Optics and Window from Berkeley Lab. The optimization routine, to solve the minimization problem with regard to the overall energy demand in relation to the switching parameters, was GenOpt from Berkeley Lab. In order to achieve some additional automation a number of command scripts were composed.

The goal of the optimization routine is to find a minimum of the overall yearly energy demand of the building by adjusting the shading parameters of upper and lower limit of external illumination for the switching algorithm as well as the shading factor itself. The optimization routine is employing a set of heuristic methods, like genetic algorithms, to find the minimum in the energy demand. It is, by the nature of the heuristic optimization method, not possible to ensure the identification of the global minimum. Although there are certain randomized procedures in place, to enable the routine to overcome local minima, the found optimum should be considered as local minimum.

We ran several scenarios of optimization. Two major scenarios will be discussed here. In the first scenario, henceforth referred to as “year specific optimization”, the shading parameters (upper and lower limit as thresholds for the switching and the shading factor) are set for a whole year. In the second scenario, from now on regarded as “month specific optimization”, the shading parameters are month specific and are adjusted each month.

Throughout all simulations we used the weather data file for Stuttgart, included in the TRNSYS data system. The temperature boundaries for the heating and cooling of the building are set so the room temperature will be kept in a comfortable range and does not drop below 20 °C and not rise above 26 °C, without any limitation on heating and cooling power consumption. The time step for the simulations is one hour and the overall time span ranges across one year. The convective heat transfer processes at the inner and outer surfaces were treated with the internal calculation routine of TRNSYS. Within this framework we investigated various building and switching configurations of which some will be introduced below.

In order to get a general impression on the capabilities of dynamic shading, the initial simulations were done on the rather generic building model depicted in Figure 4.

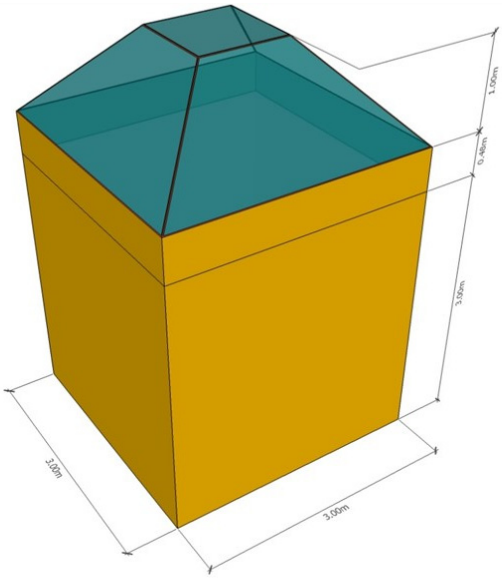

Figure 4: Generic building model with transparent roof for numerical simulation.

The generic building represents a rather oversimplified model of a field test setup, somewhat comparable to the one investigated within the Project Optima (Kaufmann 2007), than an actual building. The pneumatic cushion covers the whole roof. While this is a rather common configuration in membrane architecture e.g. for covering atria, this configuration was mainly chosen due to limitations of the building simulation tool TRNSYS in modelling transparent multi layered roof structures. The cushion itself is modelled as static and pneumatic stabilization mechanism e.g. pumps are being omitted. These simplifications were chosen to only illustrate the general correlation of energy demand and dynamic shading and the optimization routine. Further investigations on models, representing actual buildings, like a factory hall with light band roof fenestration are also in progress but will not be presented here for the sake of brevity.

 DOI: 10.3217/978-3-85125-786-1-42

The model introduced here is represented by a cube with dimensions of 3 m x 3 m x 3 m. The roof consists of a triple layered transparent construction with a curvature approximation of the outer layer of an ETFE cushion and a plane parallel middle and inner layer. The three layers of transparent roof elements were configured as fenestration components in TRNSYS, employing material data of 200 µm thick ETFE foil for the window data files. The shading mechanism was realized on the middle layer with the shading option implemented in TRNSYS. The switching of the shading is triggered by the external radiation within an upper and lower limit.

In the second configuration we implemented fenestration data into TRNSYS which was derived from spectroscopic data of two real electrochromic devices provided by project partners. The optical properties in terms of transmission, absorption and reflection coefficient in the solar and visual spectral range (T_sol/vis, Abs_sol/vis, R_sol/vis) and heat transfer properties in terms of U-value and g-value of both systems, as derived from the spectral data with the tools Optics and Window are given below in Table 2.

Table 2:
Optical and heat transfer properties of electrochromic elements.

name	T_sol	Abs_sol	Rf_sol	T_vis	Abs_vis	Rf_vis	emis_f	SHGC	U-value
econtrol-I-raw_matr_cen	0,494	0,433	0,073	0,595	0,357	0,048	0,84	0,675	5,44
econtrol-II-raw_matr_cen	0,346	0,578	0,076	0,439	0,511	0,05	0,84	0,59	5,44
econtrol-III-raw_matr_cen	0,248	0,678	0,08	0,33	0,617	0,053	0,84	0,535	5,44
econtrol-IV-raw_matr_cen	0,171	0,751	0,084	0,24	0,705	0,055	0,84	0,491	5,44
econtrol-v-raw_matr_cen	0,074	0,837	0,096	0,116	0,821	0,063	0,84	0,434	5,44

name	T_sol	Abs_sol	Rf_sol	T_vis	Abs_vis	Rf_vis	emis_f	SHGC	U-value
eelicon_I_raw_cen	0,341	0,512	0,146	0,484	0,398	0,118	0,9	0,563	5,88
eelicon_II_raw_cen	0,2	0,498	0,112	0,259	0,639	0,102	0,9	0,502	5,88
eelicon_III_raw_cen	0,204	0,587	0,092	0,144	0,762	0,094	0,9	0,514	5,88

The first electrochromic system is a commercially available system for multi pane glass windows by e-control with five stages of switchable shading which will be referred to simply as ECONTROL. The second system is a polymer based system with three shading stages, which emerged from a previous research endeavor by one of our project partners, simply referred to as EELICON.

The switching, between the different stages, is implemented into the TRNSYS simulation by conditional equation elements controlling the window ID, depending to the external irradiation on the outer surface. In addition to the temperature control via heating and cooling several auxiliary loads and gains have been introduced into the simulation, to approximate a more realistic usage scenario. These additional loads, gains and boundaries of the simulation are listed below.

- Scheduled occupation by inhabitants from 8:00 to 18:00 o'clock, Monday to Friday.
- Scheduled thermal load by technical equipment from 6:00 to 18:00 o'clock, Monday to Friday.
- Scheduled thermal and electrical load by dynamic artificial lighting during occupation. With a dynamic daylight control algorithm to provide illumination of minimum 300 lux inside, 1 m above floor level.
- Allowing the room temperature to drop to 16 °C at times without occupation.
- Constant natural infiltration with a fixed air change rate set to 0.6 h^{-1}.

The overall energy balance takes all these loads and gains into account and does also account for the energy demand of the switching processes of the electrochromic elements. The value for the energy demand of the elctrochromic elements was derived from data of a laboratory set up and might deviate up to one order of magnitude to the energy demand of commercial products. Still, this energy demand is fairly low and does not have a significant impact on the overall energy demand, as we will demonstrate in the discussion of the results. The shading rate of the different stages of the electrochromic elements is given by their optical properties, therefore the optimization routine has no influence on the shading factor itself and only manipulates the stage specific thresholds for the switching routine.

RESULTS AND ANALYSIS

In this section we display and discuss the results of the simulations and optimization processes. We compare the energy demand of the unshaded state, where all window panes consist of transparent ETFE material, to the shaded state, with the according optimized switching algorithm.

The results of the simulations of the first step, employing the TRNSYS integrated shading mechanism, omitting scheduled internal loads and

 DOI: 10.3217/978-3-85125-786-1-42

gains, are shown below, with regard to the monthly and overall yearly energy demand for heating and cooling, for the year specific and month specific optimization in Figure 5 and Figure 6 respectively.

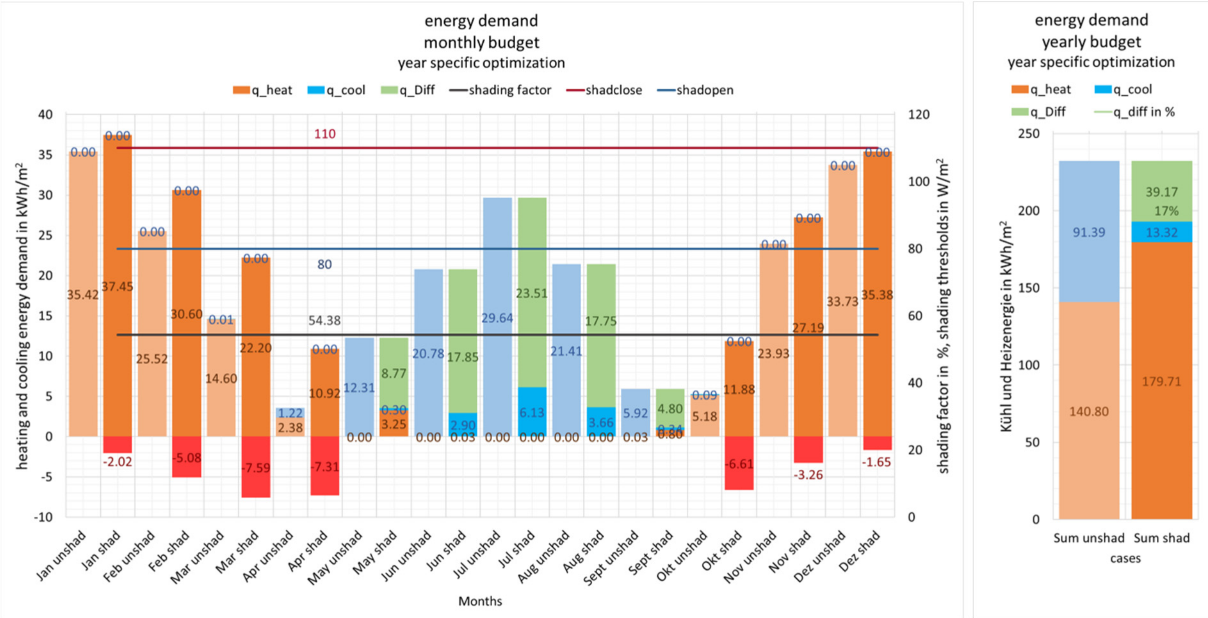

Figure 5: Energy demand for year specific optimization with TRNSYS integrated shading.

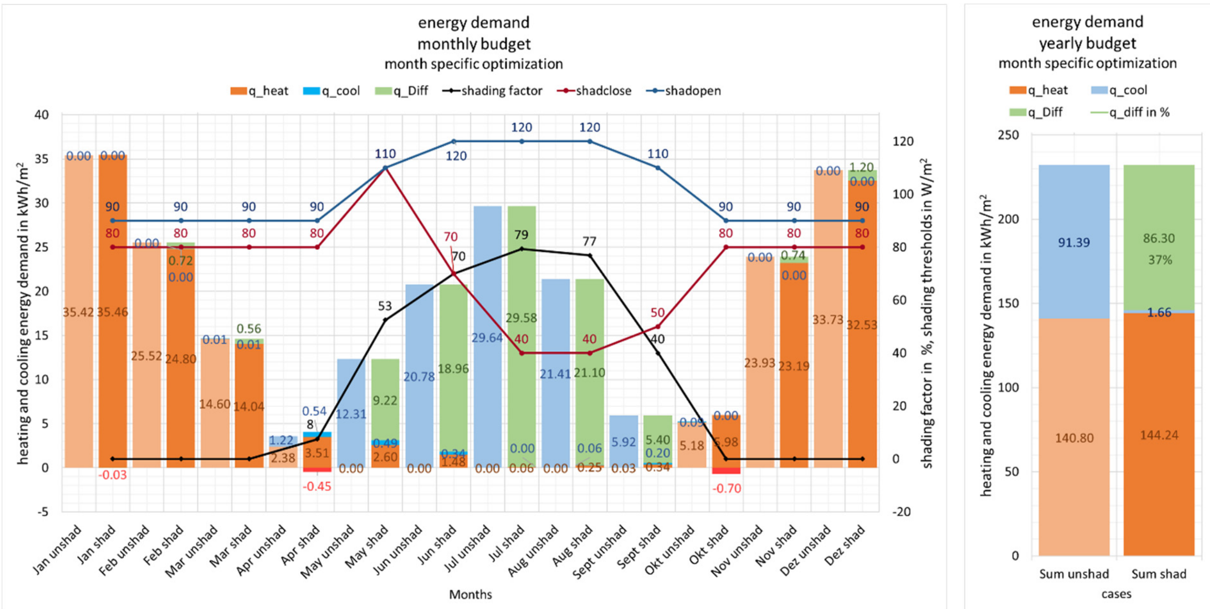

Figure 6: Energy demand for month specific optimization with TRNSYS integrated shading.

The heating and cooling energy demands are displayed as orange and blue colored columns and reductions and increases in energy demand are marked as green and red colored columns respectively.

The thresholds for the switching algorithm of the shading, as well as the maximum shading factor, are illustrated as values for each month connected by straight lines. The difference in the switching algorithm, i.e. year specific and month specific, in Figure 5 and Figure 6 becomes obvious by the variation in the course of these lines. In the case of the year specific optimization in Figrue 5, the horizontal lines represent fixed optimized values along the whole year, found by the optimization routine for the corresponding minimum in overall yearly energy demand, whereas in Figure the parameters are individually adjusted each month in the month specific optimization to achieve the lowest possible energy demand in each month.

In both cases of the optimizations, the dynamic shading results in a reasonable amount of reduction in the overall energy demand of the building of about 17 % in the year specific and 37 % in the month specific optimization, indicated by the green column shown on the right side part of the plots.

 DOI: 10.3217/978-3-85125-786-1-42

This reduction emerges completely from the decrease in heat load from external radiative energy influx and the corresponding decrease in cooling energy demand. It can also be seen that a fixed year specific threshold for the switching leads to an increase in heating energy demand during the winter time, when the outer temperature is typically below the comfortable room temperature, due to the reduction of radiative heat transfer into the building. The required shading factor for the achieved energy reduction is about 59 % in the year specific case and peaks at a maximum of about 79 % in the month specific case. This seems to be in the viable range of the real commercial elements, according to the solar transmission rate of about 7 % and about 20 % for the darkest stage of the ECONTROL and EELICON elements respectively from Table 2. In contrast to the internal shading system in TRNSYS, where the unshaded stage is simply the transparent window pane material, real electrochromic elements display a reduced solar transmission rate of about 49 % (ECONTROL) and 34 % (EELICON), which does reduce the transmitted radiative energy flux into the building even in their brightest "unshaded" state. The results of the simulation employing data from the real electrochromic elements are shown below. For the sake of brevity we will only show the results of the month specific optimization in a month resolved plot. A comparative overview of the different switching scenarios including the year specific optimization will be given further below. The results of the month specific optimization for the ECONTROL and EELICON elements are shown in Figure 7 and Figure 8 respectively.

the electrochromic switching process is also displayed as yellow and gray colored columns respectively. Additionally, to the thresholds for the electrochromic states the number of switching processes is also displayed in the plots. For both electrochromic elements a reasonable reduction in the overall energy demand of about 8 % for ECONTROL and about 22 % for EELICON elements is found. Again the reduction emerges mostly from a decrease in the cooling energy demand due to the reduced radiative heat transfer. The energy demands for artificial lighting and the switching of the electrochromic system are significantly lower than the energy demand for heating and cooling, by about one to four orders of magnitude. The aforementioned impact of the reduced transparency of electrochromic elements in general can be seen in an increase of the energy demand for heating in winter months, when no switching occurs and the electrochromic elements stay constantly in the brightest state. This is simply due to the reduced transmission rate for solar radiation of the electrochromic elements in the brightest unshaded state, in comparison to the unshaded transparent window material. This effect is overcompensated in the overall yearly energy demand. The general impact of variations in the switching strategies was demonstrated by the comparison of the results of the year specific and month specific optimization. In general one would assume that the reduction in energy demand would correlate to the resolution of the timescale of the optimization. An adaptation of the switching routine to individual, daily or even hourly environment changes might therefore result in a further reduction of the energy demand.

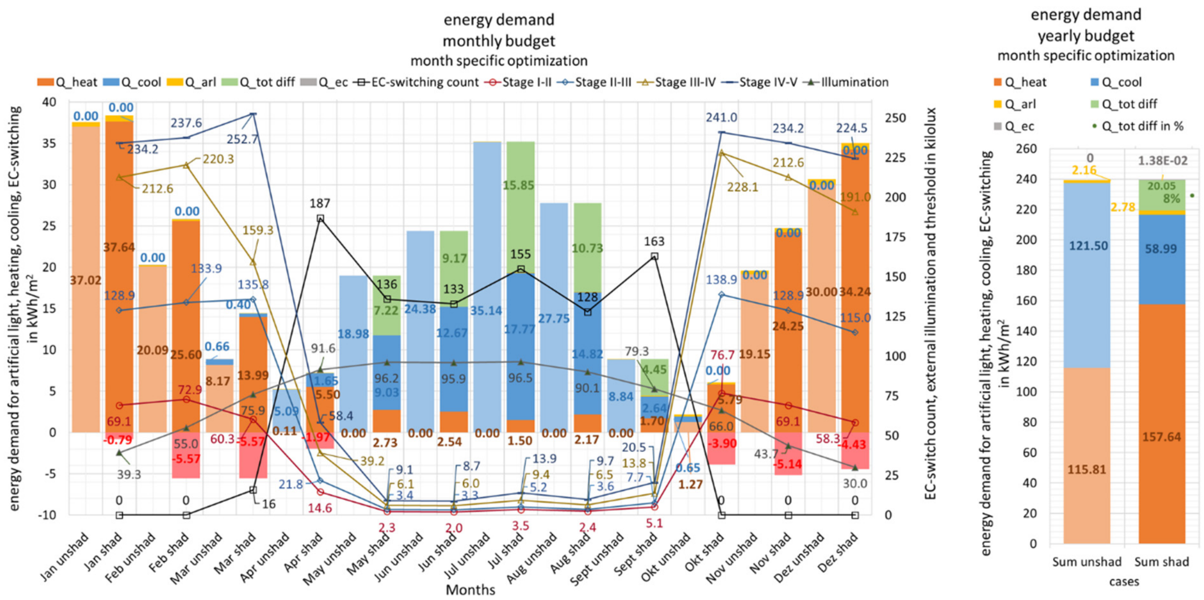

Figure 7: Energy demand for month specific optimization with ECONTROL elements.

In addition to the energy demand for heating and cooling the energy demand for artificial lighting and

 DOI: 10.3217/978-3-85125-786-1-42

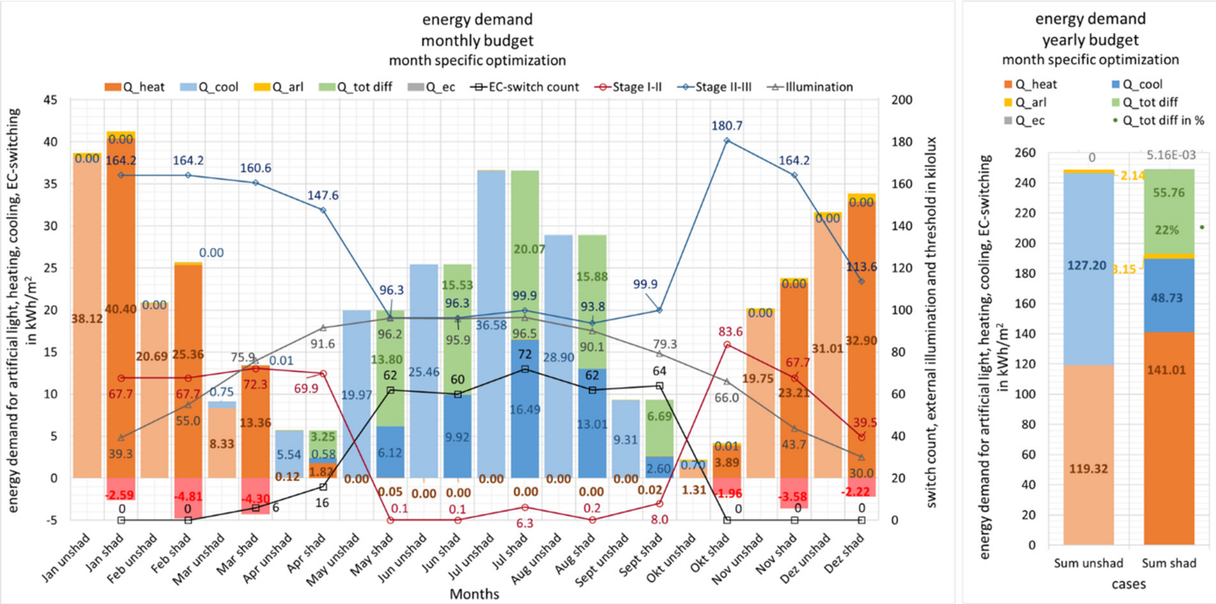

Figure 8: Energy demand for month specific optimization with EELICON elements.

In order to depict the correlation between switching strategy and energy reduction, a more comprehensive comparison of the impact of the different switching algorithms on the overall yearly energy demand is displayed below, exemplarily for the EELICON elements in Figure 9.

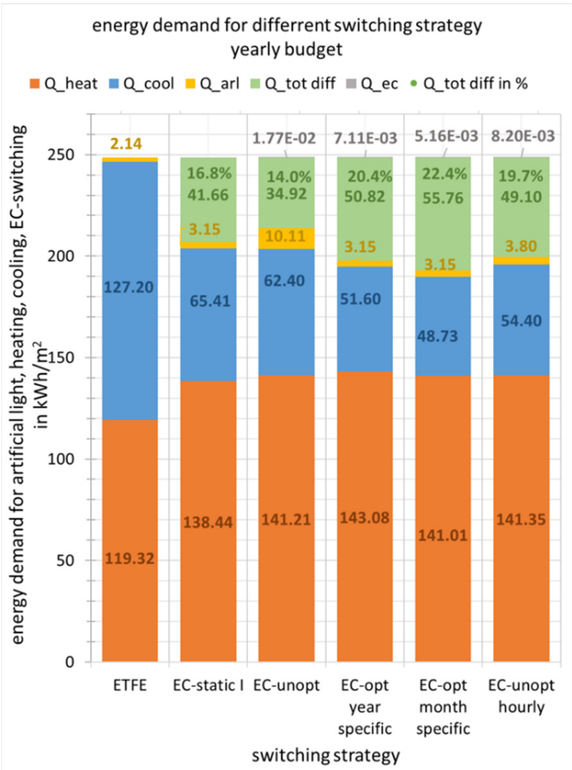

Figure 9: Energy demand for different switching algorithms with the EELICON elements.

The installation of the electrochromic elements without any switching (EC-static I) results in a reduction of the overall yearly energy demand of the building of 16.8 %. The unoptimized year specific switching strategy (EC-unopt) by identifying the thresholds simply by means of preprocessing of the numerical simulation for each shading state results in a reduction of about 14 %, whereas a switching strategy by the year specific optimization (EC-opt year specific) leads to a reduction of 20.4 %. The switching strategy by the month specific optimization (EC-opt month specific) results in a reduction of 22.4 %. At last an attempt of an hourly switching strategy was conducted (EC-unopt hourly), again by means of preprocessing the data of the numerical simulation of each shading state and manually assigning a state to every hour. This resulted in a reduction of 19.7 %. Generally a trend can be identified for a higher reduction in relation to the time resolution of the optimization. The highest potential for a reduction in energy demand is achieved with the month specific optimization.

SUMMARY AND OUTLOOK

In conclusion of the numerical investigations within this endeavor it can be stated, that dynamic shading with electrochromic elements bears reasonable potential for the reduction of the overall yearly energy demand. The adaptation of the thresholds for the switching algorithm based on month specific optimization bears prospect of higher reduction in the energy demand in comparison to adaptation based on year specific optimization. Employing a switching strategy, based on assignment of the thresholds by simple preprocessing of numerical results is slightly inferior to the optimizational approach. The overall energy demand for the electrochromic elements is typically several orders of magnitude smaller than other energy demands of the building and is therefore mostly negligible.

ACKNOWLEDGMENT

The authors would like to thank the project partners for their valuable collaboration and for providing spectroscopic data of the electrochromic elements.

The project “FLEX-G" (funding reference 03ET1470A) is funded by the German Federal Ministry for Economic Affairs and Energy (BMWI).

REFERENCES

Antretter, F., 2008. Thermal Transfer through Membrane Cushions Analyzed by Computational Fluid Dynamics, FHG-IPB, Holzkirchen.

ASTM G173-03(2012), Standard Tables for Reference Solar Spectral Irradiances: Direct Normal and Hemispherical on 37° Tilted Surface, ASTM International, West Conshohocken, PA, 2012, www.astm.org.

Cremers, J., Marx, H., 2017. Improved Daylight Comfort by a New 3D-Foil That Allows to Trade off Solar Gains and Light Individually. Structural Membranes 2017. Munich. Proceedings, p.133-140.

Cremers, J., Marx, H., 2017. 3D-ETFE: Development and evaluation of a new printed and spatially transformed foil improving shading, light quality, thermal comfort and energy demand for membrane cushion structures. Energy Procedia, Vol. 122, p. 115–120.

Flor Jan-Frederik, Dingming Liu, Yanyi Sun, Paolo Beccarelli, John Chilton, Yupeng Wu, 2018. Optical aspects and energy performance of switchable ethylene-tetrafluoroethylene (ETFE) foil cushions, Applied Energy, Volume 229, Pages 335-351, ISSN 0306-2619.

Hanam, B. et al., 2014. Energy Performance of Windows: Navigating North American and European Window Standards”, 14th Canadian Conference on Building Science and Technology-Toronto, Ontario, Canada

Jianhui Hu, Wujun Chen, Zhenyu Qiu, Bing Zhao, Jinyu Zhou, Yegao Qu, 2015. Thermal performances of ETFE cushion roof integrated amorphous silicon photovoltaic, Energy Conversion and Management, Volume 106, Pages 1201-1211, ISSN 0196-8904.

Kaufmann, A., Mitterer, C. 2007. Membrane im Bau - bauphysikalische Optimierung und neue Einsatzbereiche Kurztitel: OptiMA, Fraunhofer IBP Selbstverlag.

Knippers, J., Cremers, J., Gabler, M., & Lienhard, J. 2013. Atlas Kunststoffe + Membranen: Werkstoffe und Halbzeuge, Formfindung und Konstruktion. München: Detail.

Liebhart, H., Cremers, J., Hajek, O., Marx, H., Mirbach, D. 2019. The ideal ETFE fenestration: The influence of material properties on the thermal performance, Proceedings of the IASS Annual Symposium 2019 – Structural Membranes 2019, Form and Force 7 – 10 October 2019, Barcelona, Spain.

Manara, J. et. al, 2012. MESG: Membran-konstruktionen zur energetischen Sanierung von Gebäuden, Abschlussbericht, Würzburg 2012

Marx, H., 2018. FMESG: 'Functionalised membrane structures for energy-efficient retrofitting of buildings', Partial project: Building physics and architectural concepts, Final report, Stuttgart.

Vos, J. J. (1978). Colorimetric and photometric properties of a 2-deg fundamental observer. *Color Research and Application, 3*, pages: 125-128, 197

 DOI: 10.3217/978-3-85125-786-1-42