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Comparison of the Energy Saving Potential of Adaptive and Controllable Smart Windows

A State-of-the-Art Review and Simulation
Studies of Thermochromic, Photochromic
and Electrochromic Technologies

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Abstract

Today's building sector in the EU stands for about 40 % of the total energy consumption and about 75 % of all buildings are energy inefficient. By making both the new and the existing buildings smarter and more energy efficient, the goal is to cut CO_2 emissions by at least 40 % by 2030 and to reach a low and zero-emission building stock in the EU by 2050. This was stated in a press release made by the European Commission the 17^{th} of April 2018.

While windows play a huge role in today's buildings, allowing for outside view and providing occupants with daylight, it is also often considered to be one of the weakest building component with high thermal losses and is often the reason for overheating and glare issues. In comparison to traditional static windows, dynamic solutions like adaptive and controllable smart windows have the ability to adjust their optical properties in response to changing boundary conditions and hence have the potential to improve the energy performance and the user comfort of buildings.

The objective of this work is twofold: (1) To collect and present the state-of-the-art commercially available smart windows from manufacturers, both adaptive and controllable products, i.e. thermochromic, photochromic and electrochromic smart windows. This collection provides the reader with valuable information about window properties such as the U-value, g-value, solar transmittance (T_{sol}) and visible solar transmittance (T_{vis}). However, it is currently difficult to obtain all the desired information about the products from the manufacturers' websites and other open channels. (2) To conduct building energy performance simulations on selected products from each technology. These products are also simulated using the same U-values as the reference window, and in addition, two theoretical cases have been simulated to investigate the theoretical potential of different smart windows. Here, the optical parameters take on fictious values between 10 to 90 % and between 0 to 100 % transmittance, respectively. All cases are simulated at three different locations, i.e. Trondheim (Norway), Madrid (Spain) and Nairobi (Kenya), and are compared to a reference static window. In total, 63 cases are simulated using the simulation software package IDA Indoor Climate and Energy (IDA ICE). The results shows that the electrochromic window controlled by operative temperature has the highest potential in lowering the energy demand for all cases and locations. The study also highlights the importance of having the right control strategy and control levels for each specific case.

Preface

This master thesis was carried out Spring 2018 in association with the Department of Civil and Environmental Engineering (IBM) at NTNU and the Department of Materials and Structures at SINTEF Building and Infrastructure in Trondheim, Norway. The work concludes my five years of study and is carried out as the final requirement in the Master of Science (MSc) program of Civil and Environmental Engineering (Bygg- og miljøteknikk).

The topic for the master thesis was specified in cooperation with Bjørn Petter Jelle. The main body of this work is twofold, where the first part consist of a state-of-the-art review of commercially available adaptive (thermochromic and photochromic) and controllable (electrochromic) smart window products. The second part consist of energy performance simulations on both selected commercial products and theoretical cases where the main objective was to explore the energy saving potential of smart windows. The results are presented in the form of a scientific article which was submitted for publication in the scientific journal *Solar Energy Materials and Solar Cells* in June 2018.

I would like to direct special thanks to my supervisor Bjørn Petter Jelle for the continuous guidance throughout my research. Especially for introducing me to the topic of smart windows and for challenging me to write an article. I would also like to thank Mohamed Hamdy and Tao Gao for their advices and feedback concerning the modelling and simulations in IDA ICE and the knowledge about smart windows, respectively. Also, I would like to thank Bengt Hellström at Equa Simulation AB for all the help concerning the modelling of smart windows, and NTNU for the opportunity to participate in the IDA ICE intermediate course at the headquarters of Equa in Stockholm, Sweden. Finally I would like to thank my family and friends for the continuous support throughout this semester. Special thanks goes to my fellow student Stian Wirak with whom I have had countless of discussions with concerning the topic and giving me advices and feedback using IDA ICE.

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Process report

Introduction

This process report covers the work on the article "Comparison of the Energy Saving Potential of Adaptive and Controllable Smart Windows: A State-of-the-Art Review and Simulation Studies of Thermochromic, Photochromic and Electrochromic Technologies", written during spring 2018. The objective of this work is twofold: (1) To collect and present state-of-the-art commercially available adaptive and controllable smart window products from manufacturers, i.e. thermochromic, photochromic and electrochromic windows and (2) to conduct building energy performance simulations on selected products from each technology and additional theoretical cases.

Expectations

The bar was initially set pretty high for this master thesis. Considering that I changed my course of study from Project Management, in which I wrote my specialization project, to Building and Materials, meant that I lacked the advantage of having the theoretical foundation and the background knowledge concerning the specific topic chosen. Basic knowledge had however been obtained through other courses taken throughout my studies. Also, it was decided that the intention of this work was to write an article that would be submitted for publication in a scientific journal. This would be a new experience, since this would be my first ever written article. In addition, a large part of the work consisted of performing energy simulations, for which a suitable software package needed to be found and to be learned and to explore the possibilities. Altogether, there were many uncertainties concerning the scope and the work would definitely be a challenge. The plan was to first investigate the possibilities for modelling and simulating smart windows in various software packages, and then to choose at least one for the work. Further, products from manufacturers would be collected to present a state-of-the-art review and to conduct energy simulations on selected products and theoretical cases. A literature study was also conducted on previous work in the field of smart windows and building performance simulations.

Work progress

The first phase of the work consisted of finding a suitable software package that could be used for the modelling and simulations of both adaptive (thermochromic and photochromic) and controllable (electrochromic) smart windows. From a literature study and by consulting with professors and fellow students at NTNU it was concluded that the two software packages IDA ICE and EnergyPlus would be a suitable choice. However, due to that none of the mentioned software's had been used be the author, it turned out to be too much work to learn and conduct the simulations in both programs. therefore it was decided to continue using only IDA ICE. An intermediate course was participated in held by the providers of the software at the headquarters of EQUA Simulation AB (Stockholm, Sweden). This was a crucial part of the work were specific guidance was provided concerning the modelling of the smart windows. This turned out to be much more complicated and time consuming than anticipated, and the initial scope of the number of simulated cases was reduced.

The second phase of this work consisted of finding commercially available smart window products from manufacturers through websites and other open channels. Also, this turned out to be much harder than anticipated, since the information provided is often very limited. When as much information as possible was collected from the websites of the manufacturers', the missing information was then tried to be obtained through emails. However, only a few replies were received which resulted in an incomplete collection.

The third phase consisted of conducting energy simulations and to present the results in an article. Also, this turned out to be much more time consuming than anticipated. Even though the scope was reduced initially, the amount of work considering the simulations and post-processing and analyzing the results demanded both time and patience.

Summary

This work has been both challenging and rewarding on many levels, where many new aspects was taken on for the first time. Lesson learned is that things takes more time than first anticipated, which can sometimes be frustrating. Especially working with simulation software, were the technology does not always play along. Writing an article demand lots of work from the author concerning both the content and language but is very rewarding once the work is finished and send in for publication. This semester has been very different from what I have done in my previous studies and it has been very interesting and educational to work in the frontier of research in the chosen field.

Submitted to the scientific journal *Solar Energy Materials and Solar Cells in* June 2018

Comparison of the Energy Saving Potential of Adaptive and Controllable Smart Windows: A State-of-the-Art Review and Simulation Studies of Thermochromic, Photochromic and Electrochromic Technologies

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Abstract

Today's building sector in the EU stands for about 40 % of the total energy consumption and about 75 % of all buildings are energy inefficient. By making both the new and the existing buildings smarter and more energy efficient, the goal is to cut CO_2 emissions by at least 40 % by 2030 and to reach a low and zero-emission building stock in the EU by 2050. This was stated in a press release made by the European Commission the 17th of April 2018.

While windows play a huge role in today's buildings, allowing for outside view and providing occupants with daylight, it is also often considered to be one of the weakest building component with high thermal losses and is often the reason for overheating and glare issues. In comparison to traditional static windows, dynamic solutions like adaptive and controllable smart windows have the ability to adjust their optical properties in response to changing boundary conditions and hence have the potential to improve the energy performance and the user comfort of buildings.

The objective of this work is twofold: (1) To collect and present the state-of-the-art commercially available smart windows from manufacturers, both adaptive and controllable products, i.e. thermochromic, photochromic and electrochromic smart windows. This collection provides the reader with valuable information about window properties such as the U-value, g-value, solar transmittance (T_{sol}) and visible solar transmittance (T_{vis}). However, it is currently difficult to obtain all the desired information about the products from the manufacturers' websites and other open channels. (2) To conduct building energy performance simulations on selected products from each technology. These products are also simulated using the same U-values as the reference window, and in addition, two theoretical cases have been simulated to investigate the theoretical potential of different smart windows. Here, the optical parameters take on fictious values between 10 to 90 % and between 0 to 100 % transmittance, respectively. All cases are simulated at three different locations, i.e. Trondheim (Norway), Madrid (Spain) and Nairobi (Kenya), and are compared to a reference static window. In total, 63 cases are simulated using the simulation software package IDA Indoor Climate and Energy (IDA ICE). The results shows that the electrochromic window controlled by operative temperature has the highest potential in lowering the energy demand for all cases and locations. The study also highlights the importance of having the right control strategy and control levels for each specific case.

Keywords: Smart window, Thermochromic, Photochromic, Electrochromic, Energy saving, Simulation

1 Introduction

On the 17th of April 2018, the European Commission gave out a press release on the new revised Energy Performance of Buildings Directive, approved by the European Parliament (Commission, 2018). This approval signals the closure of the first eight legislative proposals part of the "Clean Energy for All Europeans" package and is a key element of one of the Juncker Commission's priorities, "a resilient Energy Union and a forward-looking climate change policy". Today's building sector in the EU stands for about 40 % of the total energy consumption and about 75 % of all buildings are energy inefficient. By making new and existing buildings smarter and more energy efficient, the goal to cut CO_2 emissions by at least 40 % by 2030 and the path towards a low and zero-emission building stock in the EU by 2050 (Commission, 2018), are closer achievable.

Windows are an important building element in today's buildings. It provides the occupants with daylight and outside view, which have been proven to be important for a human's well-being. At the same time, windows are often considered as a large thermal bridge at the building envelope with high thermal losses. In addition, windows can bring with overheating and glare issues. In recent years, the window performance has been improved significantly through different window and glazing technologies, such as multilayered (e.g. double or triple) glazings and the use of several types of coatings, which in general make windows more energy efficient (Jelle et al., 2012). Traditional windows are normally a static building component, whereas the climate is in a continuous shifting state with changing temperatures and solar radiation. Hence, the tradeoff between allowing positive solar heat gain, daylight and outside view, while preventing glare and overheating, is challenging. Accessory solar shading devices such as blinds or curtains are often used; alternatively, advanced window technologies such as dynamic windows are under rapid development due to their abilities to change the optical properties in response to the climate or the user requirements. These windows are often called "smart windows" and can be divided into different categories, namely, chromic windows (thermochromic, photochromic and electrochromic), liquid crystals and suspended-particle devices (Baetens et al., 2010). In this work, the chromic windows will be investigated, and they will in the following be mentioned as smart windows. Smart windows may also be part of the multi-functional building envelopes of the future (Jelle et al., 2018).

Many studies can be found on the electrochromic windows, while few can be found on thermochromic and photochromic windows. The fact that different smart window technologies are available at the market and new materials and devices are also under rapid development may call for a comparison study to reveal the potential of the different smart windows. In a previous study made by Mäkitalo (2013), the impact of electrochromic windows with various control strategies was simulated for an office building in Stockholm, Sweden using the simulation software package IDA ICE (EQUA Simulation AB, 2018g). It was demonstrated that electrochromic windows yielded a better energy performance than regular windows with blinds. It was also shown through a sensitivity analysis that the tinting speed of the electrochromic windows has little or no effect on the buildings energy performance. Further, Reynisson (2015) studied the energy performance of electrochromic windows in various cities in Europe using a combination of the control strategies originally created by Mäkitalo (2013). The study showed that the energy consumption could be lowered by 10-30 % compared to a window with operable blinds and up to 50-75 % compared to a window without blinds depending on location. It was also concluded that electrochromic windows have a larger impact on the energy performance in warmer climates. Ajaji and Andre (2016) investigated the impact of electrochromic windows in an office building in Brussels. Energy simulations were conducted, and it was shown that primary energy consumption was reduced from 100.9 kWh/m^2 to 38.6 kWh/m^2 when controlling the windows by outdoor temperature and illuminance. The main cut in energy consumption was due to a lower cooling demand. In addition, climate adaption and the implementation of suitable control strategies are important for maximizing the energy efficiency of switchable glazings, as reported in a recent review of active dynamic windows for buildings (Casini, 2018). It was concluded that electrochromic windows is the present most mature technology and can improve visual and thermal comfort as well as the energy performance of buildings. The importance of the control range for the visual specter and the light-to-solar gain ratio was also highlighted. Piccolo et al. (2018) investigated the impact of electrochromic windows controlled by illuminance on a residential building compared to a reference window for two locations. It was found that the largest energy saving potential is in warmer climates and with a higher window-to-wall ratio due to a reduced cooling demand. This was also in accordance with experimental findings conducted in the same study. Dussault and Gosselin (2017) conducted a sensitivity analysis to address the relative effect of the main building design parameters on energy comfort improvements related to the use of smart windows. Energy simulations was performed for an office building for various combination of the design parameters: location, façade orientation, window control, window-to-wall ratio, internal gains, thermal mass and envelope tightness. Also here, the conclusions are that the largest energy saving potential is due to a reduced cooling demand in warmer climates and higher solar radiation exposures. For further information about miscellaneous electrochromic materials and devices it is referred to the available literature, see e.g. the studies by Granqvist et al. (2010), Granqvist (2012), Jelle et al. (1993), Jelle and Hagen (1993), Jelle et al. (1998), Jelle et al. (2007), Jelle (2013), Lampert (1984), Lampert (1998), Monk et al. (1995), Mortimer et al. (2006) and Mortimer et al. (2015).

The objective of this work is twofold: (1) To collect and present state-of-the-art commercially available smart window products on today's market and (2) to conduct energy performance simulations of selected products from this collection and for three theoretical cases. The products have been collected from manufacturers mainly through websites and represent both adaptive (thermochromic and photochromic) and controllable (electrochromic) smart windows. The collection provides the reader with information valuable for energy performance of smart windows, e.g. U-value, g-value (also called solar factor (SF) and solar heat gain coefficient (SHGC)), solar transmittance (T_{sol}) and visible solar transmittance (T_{vis}). Definitions can be found in Jelle (2013). However, the collection is not complete due to missing information not available from the manufacturers. Hopefully, this work can serve as an incentive for manufacturers to provide the necessary information and for customers to demand these.

From the list of products, three smart window technologies, namely, thermochromic window (TCW), photochromic window (PCW) and electrochromic window (ECW), have been simulated using IDA ICE and their impact on the energy performance of a building has been compared for three different locations, i.e. Trondheim (Norway), Madrid (Spain) and Nairobi (Kenya). The ECW are simulated using three different control strategies based on operative temperature, indoor daylight and solar radiation. The work presents many tables and diagrams with a lot of information concerning simulations setup, control strategies and results. In addition to "real cases", each technology has also been simulated for three fictious cases. The real cases are simulated with the same U-value as for the reference window, denoted "real cases with same U-value". Further, theoretical and more ideal cases are simulated with transmittance regulations between 10 to 90 % and between 0 to 100 %, denoted Range 10-90 and Range 0-100, respectively. The theoretical cases are included in the study to investigate the theoretical potential of smart windows, where all technologies take on the same optical properties and only the control strategies separates them.

2 Commercial smart window products

The first main objective for this study is to collect information about commercial smart window products available on today's market. Smart windows can be defined by several factors such as the optical properties, heat transfer coefficient, durability, switching times etc. Due to that the second main objective of this study is to perform energy simulations, the focus has been on collecting the most crucial factors for this purpose, i.e. U-value, g-value, T_{sol} and T_{vis}. Other valuable information presented about the products are the switching levels, i.e. temperature switching levels for TCW and solar radiation switching levels for PCW, switching times, durability, electric demand (ECW), maximum size of window products and additional material specifications.

In the following subchapters, products of thermochromic, photochromic and electrochromic windows along with their various properties have been collected and presented in comprehensive tables (Tables 1-3). These tables add information to previous studies made by Baetens et al. (2010) and Jelle et al. (2012). The products are divided into technology and manufacturer. It is currently hard to obtain all the desired information from all the manufacturer's websites or other open information channels. It is especially difficult to find information concerning control strategies and control levels for all smart windows. Fields that are missing information about the U-value, g-value, T_{sol}, and T_{vis} mean that information could not be found from the manufacturer. Other information can be found in "Further information". The reader may also find additional information about the products on the respective websites of the manufacturers.

2.1 Thermochromic window products

Information about the TCW is relative easy to find through the manufacturers' websites and other open channels. However, some information is missing from some manufacturers. From Table 1, the following can be observed:

- The g-value vary between 0.62-0.2 for the clearest state and between 0.449-0.1 for the darkest state.
- T_{sol} vary between 0.499-0.1 for the clearest state and between 0.416-0.2 for the darkest state.
- T_{vis} vary between 0.6-0.27 for the clearest state and between 0.12-0.6 for the darkest state.
- Information about control levels are missing from some manufacturers.

Note that the highest and lowest values for the clearest and darkest state does not occur for the same product. The largest span for the g-value is 0.21, while most spans lies between 0.10-0.15. The largest span for T_{sol} is 0.18, while most spans lies between 0.10-0.15. The largest span for T_{vis} is 0.5, while most spans lies between 0.25-0.45. Often the window has a low U-value when the transmittance values are low and vice versa. The U-values vary between 2.76-1.31 ($W/(m^2K)$) depending on the product and the number of window panes. All commercial TCW products are presented in Table 1.

Table 1. Commercial TCW products collected from manufacturers. Empty spaces is due to missing information from the producers.

Manufacturer	Product	U_g (W/(m^{2}K))	T_{vis}	T_{sol}	g-value	Further Information
Pleotint LLC, 6722 18th Ave, Jenison, MI 49428, USA. Tel.: +1 616 662 7216. fax: +1 616 662 7215. www.pleotint.com info@pleotint.com 	Solargray+ Suntuitive with Solarban® 60	1.36	0.30-0.06	0.14-0.04	0.24-0.13	[Accessed 26.06.2014]. Thermochromic windows for building applications. 10 years warranty. Passed ASTM E2141-06. Continuous transition. Switching time: 20-30 min, Durability: 20 years, Electrical demand: 0, Max size: 165.1 cm witdh, Switching temperatures: Clearest = 10°C, Darkest = 65°C.
	Solargray+ Suntuitive with Solarban®70XL	1.31	0.27-0.06	0.10-0.03	0.20-0.11	
	Solarbronze+ Suntuitive with Solarban® 60	1.36	0.36-0.08	0.16-0.05	0.26-0.14	
	Solarbronze+ Suntuitive with Solarban®70XL	1.31	0.33-0.07	0.12-0.03	0.22-0.11	
	Solarblue+ Suntuitive with Solarban® 60	1.36	0.38-0.08	0.16-0.05	0.27-0.14	
	Solarblue+ Suntuitive with Solarban®70XL	1.31	0.35-0.07	0.13-0.03	0.23-0.12	
	Optiblue+ Suntuitive with Solarban® 60	1.36	0.43-0.09	0.20-0.06	0.31-0.16	
	Optiblue+ Suntuitive with Solarban®70XL	1.31	0.39-0.08	0.15-0.04	0.26-0.12	
	Azuria+ Suntuitive with Solarban® 60	1.36	0.46-0.10	0.16-0.04	0.26-0.12	
	Azuria+ Suntuitive with Solarban®70XL	1.31	0.42-0.09	0.14-0.03	0.24-0.11	

Table 1. Commercial TCW products continued.

Manufacturer	Product	U_g $(W/(m^2K))$	T_{vis}	T_{sol}	g-value	Further Information
Pleotint LLC, 6722 18th Ave, Jenison, MI 49428, USA. Tel.: +1 616 662 7216. fax: +1 616 662 7215. www.pleotint.com info@pleotint.com	Clear+ Suntuitive with Solarban® 60	1.36	0.60-0.13	0.26-0.08	0.37-0.17	
	Clear+ Suntuitive with Solarban®70XL	1.31	0.55-0.11	0.20-0.05	0.31-0.14	
RavenBrick, LLC, 3950 Kearney Street, Denver, CO 80207, USA, www.ravenbrick.com	1-inch IGU w/ Standard lowE	1.99	0.342-0.051	0.416-0.285	0.576-0.449	[Accessed 20.04.2018]. Thermochromic windows for building applications. 10 years warranty. Durability: 30 years. Electrical demand: 0, Switching temperatures: customized temperature ranges.
	1-inch IGU w/ Standard lowE (Gas Filling)	1.74	0.342-0.051	0.416-0.285	0.576-0.449	
	1-inch IGU w/ Double Silver lowE	1.63	0.292-0.043	0.121-0.030	0.221-0.108	
	1-inch IGU Clear Dual Pane	2.76	0.368-0.055	0.499-0.357	0.620-0.499	
Prelco, 94 Boulevard Cartier, Rivière-du-Loup (Québec), CANADA, G5R 2M9. Tel.: +1 800 463 1325. fax: +1 418 86 8181. prelco@prelco.ca. www.prelco.ca		1.36	0.60-0.13	0.26-0.08	0.37-0.17	[Accessed 26.02.2018]. Thermochromic windows for building applications. Passed ASTM G155-05a and ASTM E2141-06. Continuous transition. Switching time: 20-30 min, Durability: 20 yeras, electrical demand: 0, Max size: 165x366 cm, Switching temperatures: Clear = 25°C, Darkest = 65°C.
	Prel-Shade with green tinted and Loe² 272	1.36	0.53-0.08	0.25-0.07	0.37-0.16	
	Prel-Shade with Loe^3 366	1.31	0.48-0.07	0.17-0.03	0.23-0.10	

Table 1. Commercial TCW products continued.

Manufacturer	Product	U_g (W/(m^{2}K))	T_{vis}	T_{sol}	g-value	Further Information
Magic Glass Limited, Unit 8, Lawnhurst Trading Estate Ashurst Drive, Cheadle, Cheshire SK3 0SD, UNITED KINGDOM. Tel.: +44 (0)161 495 3650. fax: +44 (0)161 495 3651. magicglass@magicglass.co.uk. www.magicglass.co.uk	Magic Glass SRT		0.60-0.10		… - 0.11	[Accessed 26.06.2014]. Continuous transition.
Innovative Glass Corp., 130 Newtown Road, Plainview, New York 11803, USA. Tel.: +1 516 777 1100. fax: +1 516 777 1106. info@InnovativeGlassCorp.com. www.InnovativeGlassCorp.com	Solar Smart 1" Window IGU with SN68	1.46	0.57-0.12	0.25-0.08	0.37-0.18	[Accessed 22.02.2018]. Continuous transition. Switching time: 30 min, Durabilty: -22 - 160°C, Electrical demand: 0, Max size: 152.4x304.8 cm, Switching temperatures: Clearest =10°C, Darkest = 65°C
	Solar Smart 1" Window IGU with SN68	1.46	0.42-0.09	0.18-0.06	0.30-0.16	
	Solar Smart 1" Window IGU with SN68	1.46	0.29-0.06	0.13-0.04	0.24-0.14	
	Solar Smart 1" Window IGU with SN68	1.46	0.35-0.07	0.15-0.05	0.27-0.15	
	Solar Smart 1" Window IGU with SN68	1.46	0.44-0.09	0.16-0.04	0.26-0.13	
	Solar Smart 1" Window IGU with SNX62	1.42	0.52-0.11	0.18-0.04	0.32-0.15	
	Solar Smart 1" Window IGU with SNX62	1.42	0.38-0.08	0.13-0.03	0.26-0.13	

Table 1. Commercial TCW products continued.

Manufacturer	Product	U_g (W/(m^{2}K))	T_{vis}	T_{sol}	g-value	Further Information
Innovative Glass Corp., 130 Newtown Road, Plainview, New York 11803, USA. Tel.: +1 516 777 1100. fax: +1 516 777 1106. info@InnovativeGlassCorp.com. www.InnovativeGlassCorp.com	Solar Smart 1" Window IGU with SNX62	1.42	0.26-0.06	0.09-0.02	0.21-0.12	[Accessed 22.02.2018]. Continuous transition. Switching time: 30 min, Durabilty: -22 - 160°C, Electrical demand: 0, Max size: 152.4x304.8 cm, Switching temperatures: Clearest =10°C, Darkest = 65°C
	Solar Smart 1" Window IGU with SNX62	1.42	0.31-0.07	0.10-0.03	0.23-0.12	
	Solar Smart 1" Window IGU with SNX62	1.42	0.40-0.09	0.13-0.03	0.25-0.12	
	Solar Smart 7/8" Window IGU with SN68	1.46	0.59-0.12	0.27-0.09	0.39-0.19	
	Solar Smart 7/8" Window IGU with SN68	1.46	0.50-0.11	0.27-0.09	0.39-0.19	
	Solar Smart 7/8" Window IGU with SN68	1.46	0.40-0.09	0.19-0.06	0.30-0.16	
	Solar Smart 7/8" Window IGU with SN68	1.46	0.45-0.09	0.21-0.07	0.32-0.16	
	Solar Smart 7/8" Window IGU with SN68	1.46	0.51-0.11	0.20-0.05	0.31-0.14	
	Solar Smart 7/8" Window IGU with SNX62	1.42	0.54-0.11	0.19-0.05	0.33-0.15	
	Solar Smart 7/8" Window IGU with SNX62	1.42	0.46-0.10	0.16-0.04	0.29-0.14	

Table 1. Commercial TCW products continued.

Manufacturer	Product	U_g $(W/(m^2K))$	T_{vis}	T_{sol}	g-value	Further Information
Innovative Glass Corp., 130 Newtown Road, Plainview, New York 11803, USA. Tel.: +1 516 777 1100. fax: +1 516 777 1106. info@InnovativeGlassCorp.com. www.InnovativeGlassCorp.com	Solar Smart 7/8" Window IGU with SNX62	1.42	0.37-0.08	0.13-0.03	0.26-0.13	
	Solar Smart 7/8" Window IGU with SNX62	1.42	0.41-0.08	0.14-0.03	0.27-0.13	
	Solar Smart 7/8" Window IGU with SNX62	1.42	0.46-0.10	0.15-0.03	0.28-0.13	
GESIMAT GmbH, Köpenicker Str. 325, 12555 Berlin, GERMANY. Tel.: +49 (0)30 473 89 25 1; fax: +49 (0)30 473 89 252. kontakt@gesimat.de 						[Accessed 26.06.2014]. Passed DIN EN ISO 12543-4. Continuous transition. Max size: 106x253 cm
Smartglass International, Switchable Glass Solutions, Unit S3B Le Brocquy Ave, Park West IndustrialEstate, Dublin 12, IRELAND. Tel.: +353 1 620 5000. info@smartglassinternational.com.	Self-Tinting Smartglass					[Accessed 26.06.2014]

2.2 Photochromic window products

Information about the PCW is difficult to obtain through the manufacturers' websites and other open channels, hence lot of information is missing concerning both the U-value and the optical parameters. From the list of products with information, it can be seen that there is a big difference in the optical properties for the PCW. From Table 2, the following can be observed:

- The g-value vary between 0.48-0.31 for the clearest state and 0.41-0.22 for the darkest state.
- T_{vis} vary between 0.78-0.13 for the clearest state and 0.73-0.09 for the darkest state.
- The information about T_{sol} is very limited, and most of the values are missing.
- The information about control levels are missing from all manufacturers.

Note that the highest and lowest values for the clearest and darkest state does not occur for the same window. Depending on the product, there is a large variation of the highest and lowest values for the clearest and darkest state, respectively. However, the interval between the clearest and darkest state are very narrow for most products with a maximum span of 0.09 for the g-value and 0.17 for T_{vis}. The majority of the span for T_{vis} lies however between 0.1-0.9. Also, few U-values were found, and the ones listed are significantly high and vary between 5.7-5.9 ($W/(m^2K)$). All commercial PCW products are presented in Table 2.

Table 2. Commercial PCW products collected from manufacturers. Empty spaces is due to missing information from the producers.

Manufacturer	Product	U_g (W/(m^{2}K))	T_{vis}	T_{sol}	g-value	Further Information
Chameleon, No.2, Jalan Kilang 51/206, 46050 Petaling Jaya, Selangor Darul Ehsan, MALAYSIA. Tel.: +60 3 7770 6688 / 6868. fax: +60 3 7770 6689. info@cardeas.com.my. www.ndfos.com 	Chameleon 10		0.13-0.10		0.31-0.22	[Accessed 27.06.2014]. Photochromic films for automotive, architectural and residential applications. 6 years warranty. Switching time: 15-20 min, > 1h to revise back to original, Electric demand: 0.
	Chameleon 30		0.33-0.30		0.32-0.25	
	Chameleon 53		0.52-0.42		0.40-0.36	
	Chameleon 50		0.52-0.42		0.36-0.34	
	Chameleon 60		0.65-0.55		0.42-0.38	
NDFOS Window Film, 3F, Seon Am B/D, Yangpyeongdong-1Ga, Yougdengpo-Gu, Seoul (Zip: 150-862), KOREA. Tel.: +82 2 782 7790 /4. fax: +82 2 786 3480. ntech@ntechgood.com. www.ndfos.com 	N-Cool IR 9060	5.9	0.699	0.508	0.45	[Accessed 30.06.2014]. Photochromic Nano Ceramic Film for automotive applications. Original values and standard size. Electric demand: 0, Max size: 152.4x183 cm
	N-Cool CIR9050		0.56	0.326	0.28	
	Ceramic IR 9030	5.7	0.302	0.10	0.22	
	Ceramic IR 9020	5.7	0.247	0.14	0.20	
	Ceramic IR 9010	5.7	0.15	0.09	0.18	

Table 2. Commercial PCW products continued.

Manufacturer	Product	U_g $(W/(m^2K))$	T_{vis}	T_{sol}	g-value	Further Information
Tint Station Window Films PTE LTD, 50 Serangoon North Avenue 4, #03-10 First Centre, SINGAPORE. Tel.: +65 6570 4842. fax: +65 6570 4843. tintstationmike@gmail.com. sales@tintstation.com. www.tintstation.com 	Illume 20		0.16-0.09		0.31-0.22	[Accessed 30.06.2014]. Distributor of Illume™: www.illumefilm.com. [Accessed 30.06.2014]. Photochromic films for architectural building and automotive applications. Switching time: 10-15 min, Electrical demand: 0.
	Illume 30		0.28-0.23		0.33-0.25	
	Illume 40		0.37-0.30		0.36-0.28	
	Illume 50		0.45-0.37		0.40-0.34	
	Illume 60		0.56-0.47		0.42-0.36	
	Illume 70		0.70-0.63		0.47-0.38	
	Illume 80		0.78-0.73		0.48-0.41	
	Illume 50R		0.53-0.45		0.41-0.35	
	Illume 60R		0.63-0.46		0.42-0.36	
	Illume 70R		0.69-0.57		0.43-0.37	

2.3 Electrochromic window products

The information about the ECW is easier accessible through manufacturers' websites and other open channels, hence less information about the products is missing. From Table 3, the following can be observed:

- The g-value vary between 0.63-0.27 for the clearest state and between 0.31-0.04 for the darkest state.
- T_{sol} vary between 0.52-0.19 for the clearest state and between 0.06-0.01 for the darkest state.
- T_{vis} vary between 0.75-0.35 for the clearest state and between 0.17-0.01 for the darkest state.

It can be seen that the ECW has the largest span for all the optical parameters compared to both the TCW and the PCW. Note that the highest and lowest values for the clearest and darkest state does not occur for the same window. The largest span for the g-value is 0.38, while most spans lies between 0.25-0.37. The largest span for T_{sol} is 0.46, while most spans lies between 0.2-0.36. The largest span for T_{vis} is 0.67, while most spans lies between 0.4-0.55. Note that all spans for all optical parameters are largest for the ECW compared to both the TCW and the PCW. The maximum U-value is 5.5 ($W/(m^2K)$) and the minimum is 0.5 ($W/(m^2K)$), most values lies however in the span of 1-1.6 ($W/(m^2K)$) depending on the amount of window panes. All commercial ECW products are presented in Table 3.

In addition, the optical properties for the commercial ECW products can be compared to a previous study made by Jelle (2013), where spectroscopial measurements were made on three different ECW devices at various coloration levels. Here it was shown g-value ranging between 0.79-0.37 with a span of 0.42 (ECW1), and between 0.69-0.31 with a span of 0.38 (ECW2) and 0.74-0.30 with a span of 0.44 (ECW2). T_{sol} values ranges between 0.74-0.17 with a span of 0.57 (ECW1), and 0.61-0.10 with a span of 0.51 (ECW2) and 0.67-0.08 with a span of 0.59 (ECW3). T_{vis} values ranges between 0.78-0.17 with a span of 0.61 (ECW1), and 0.62-0.1 with a span of 0.52 (ECW2) and 0.69-0.09 with a span of 0.6 (ECW3).

Table 3. Commercial ECW products collected from manufacturers. Empty spaces is due to missing information from the producers.

Manufacturer	Product	U_g ($W/(m^2K)$)	T_{vis}	T_{sol}	g-value	Further Information
SAGE Electrochromics, Inc., 2 Sage Way, Faribault, MN 55021, USA; Tel.: +1 877 724 3321; fax: +1 507 333 0145; info@sageglass.com; www.sageglass.com	Classic ™ Tempered	1.59	0.62-0.02	0.38-0.007	0.47-0.09	[Accessed 24.06.2014]; Electrochromic windows for building applications. 10 years warranty. Only commercially available smart windows for exterior applications which passed ASTM E-2141-06. Tuv = 0.0 % PVB laminate. WO3-based. Ug: Summer values given. Switching time: 15-20 min (medium size), Durability: 100 000 cycles, 30 years, -30-60°C, Electrical demand: <5 VDC, Max size: 152.4x304.8 cm
	Classic ™ Tempered Laminated	1.59	0.62-0.02	0.38-0.007	0.47-0.09	
	See Green ™ (double glass)	1.59	0.48-0.028	0.19-0.01	0.44-0.09	
	Cool View Blue ™ (double glas)	1.59	0.40-0.023	0.30-0.01	0.46-0.09	
	Clear-as-Day ™(double glas)	1.59	0.35-0.019	0.29-0.01	0.46-0.09	
	Classic™ Triple Glass Ar	1.25	0.55-0.01	0.31-0.006	0.42-0.07	90 % Ar, 1 ¾'' overall thickness
	Classic™ Triple Glass Kr	1.14	0.55-0.001	0.31-0.006	0.42-0.06	95 % Kr, 1 ½'' overall thickness
	Classic™ Triple Glass Ar*	0.85	0.51-0.01	0.29-0.006	0.39-0.05	90 % Ar, 1 ¾'' overall thickness, *Additional low-e coating
	Classic™ Triple Glass Kr*	0.74	0.51-0.01	0.29-0.006	0.39-0.04	95 % Kr, 1 ½'' overall thickness, *Additional low-e coating
	SAGEGLASS CLEAR (double glass)	1.59	0.60-0.01	0.33-0.004	0.41-0.09	[Accessed 12.03.2018]. 90% Argon.

Table 3. Commercial ECW products continued.

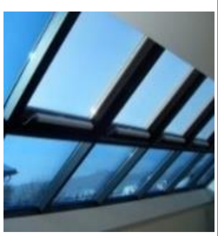
Manufacturer	Product	U_g $(W/(m^2K))$	T_{vis}	T_{sol}	g-value	Further Information
SAGE Electrochromics, Inc., 2 Sage Way, Faribault, MN 55021, USA; Tel.: +1 877 724 3321; fax: +1 507 333 0145; info@sageglass.com; www.sageglass.com	SAGEGLASS BLUE (double glass)	1.65	0.40-0.01	0.21-0.003	0.30-0.10	[Accessed 12.03.2018]. 90% Argon.
	SAGEGLASS GRAY (double glass)	1.65	0.45-0.01	0.23-0.002	0.33-0.10	
	SAGEGLASS GREEN (double glass)	1.65	0.49-0.01	0.18-0.003	0.27-0.10	
EControl-Glas GmbH & Co. KG, Otto-Erbert-Str. 8, D - 08527 Plauen, GERMANY, Tel.: +49 (0)3741 148 20-0, fax: +49 (0)3741 148 20-150, info@econtrol-glas.de, www.econtrol-glas.de	EControl® Double Glass	1.1	0.55-0.15		0.40-0.12	[Accessed 24.06.2014], Electrochromic windows for building applications. According to DIN EN ISO 12543-4 for exterior insulating glass. WO3-based. 5 years warranty. For atria, glass roofs and winter gardens. Switching time: 15-20 min, Durability: 40 000 cycles. >20 years, Electrical demand: <5 VDC. 1.5 W/m², Max size: 135x330 cm
	EControl® Triple Glass	0.5	0.48-0.13		0.33-0.09	
	EControl smart® Double glass	1.1	0.50-0.10		0.38-0.10	
	EControl smart® Triple glass	0.5	0.45-0.09		0.33-0.08	
	Econtrol ® Smart Double glass	1.1	0.56-0.10		0.42-0.10	[Accessed 12.03.2018]. Krypton-gas filling
	Econtrol ® Smart Triple glass	0.5	0.51-0.09		0.36-0.08	

Table 3. Commercial ECW products continued.

Manufacturer	Product	U_g (W/(m^{2}K))	T_{vis}	T_{sol}	g-value	Further Information
VIEW Inc., 195 South Milpitas Bd. Milpitas, CA 95035, USA. Tel.: +1 408 263 9200. info@viewglass.com. www.viewglas.com 	Standard Dual Pane IGU	1.65	0.58-0.03	0.37-0.01	0.46-0.09	[Accessed 25.06.2014]. Electrochromic windows for building applications. Passed ASTM E-2141, SGCC, IGCC/IGMA. 10 years warranty. Durability: >50 000 cycles, 50 years, 85°C. Max size: 152.4x304.8 cm
	Dual IGU with Blue Tint (double glass)	1.65	0.36-0.02	0.22-0.01	0.43-0.09	
	Dual IGU with Gray Tint (double glass)	1.65	0.42-0.02	0.26-0.01	0.44-0.09	
	Dual IGU w/ LowE on #3 (double glass)	1.36	0.49-0.03	0.22-0.01	0.33-0.07	
	Dual IGU w/ LowE on #4 (double glass)	1.31	0.57-0.03	0.35-0.01	0.43-0.08	
	Dual Lami IGU (double glass)	1.65	0.58-0.03	0.37-0.01	0.46-0.09	90% Ar.
	Dual IGU High Altitude* (double glass)	1.87	0.58-0.03	0.37-0.01	0.46-0.11	100% air, * >2500 ft
	Dual Lami IGU High Altitude* (double glass)	1.87	0.58-0.03	0.37-0.01	0.46-0.11	* >2500 ft
	Dual IGU High Alt.* with LowE (double glass)	1.48	0.57-0.03	0.35-0.01	0.43-0.09	* >2500 ft
	Triple IGU (triple glass)	1.19	0.52-0.03	0.30-0.01	0.41-0.07	2x 90% Ar

Table 3. Commercial ECW products continued.

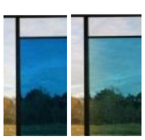
Manufacturer	Product	U_g (W/(m^{2}K))	T_{vis}	T_{sol}	g-value	Further Information
VIEW Inc., 195 South Milpitas Bd. Milpitas, CA 95035, USA. Tel.: +1 408 263 9200. info@viewglass.com. www.viewglas.com	Triple IGU with LowE on #5 (triple glass)	0.79	0.44-0.02	0.19-0.01	0.31-0.05	2x 90% Ar
	Triple IGU with LowE on #6 (triple glass)	0.97	0.51-0.03	0.29-0.01	0.31-0.05	2x 90% Ar
	Dual IGU with LowE (Europe)* (triple glass)	1.2	0.58-0.03	0.38-0.02	0.44-0.06	90% Ar, * Thicker, another LowE coating
	Triple IGU with LowE on #5 (Europe)* (triple glass)	0.7	0.52-0.03	0.32-0.01	0.39-0.04	
	Triple Lami IGU with LowE on #4 (Europe)* (triple glass)	0.7	0.52-0.03	0.32-0.01	0.39-0.04	
GESIMAT GmbH, Köpenicker Str. 325, 12555 Berlin, GERMANY. Tel.: +49 (0)30 473 89 25 1; fax: +49 (0)30 473 89 252. kontakt@gesimat.de. www.gesimat.de 			0.75-0.08	0.52-0.06		[Accessed 24.06.2014]. Electrochromic window based on EC and active counter-EC. WO3+active CE. Switching time: 10 min, Electrical demand: 1-3 VDC, Max size: 100x240 cm

Table 3. Commercial ECW products continued.

Manufacturer	Product	U_g $(W/(m^2K))$	T_{vis}	T_{sol}	g-value	Further Information
ChromoGenics AB, Märstagatan 4, SE-75323, Uppsala, SWEDEN. Tel.: +46 (18) 430 04 30. fax: +46 (18) 123 224. info@chromogenics.com. www.chromogenics.com 	Conver Light™ Single glass	5.5	0.66-0.17		0.63-0.31	[Accessed 12.03.2018]. Granqvist (2011).Two polyethylene terephthalate (PET) foils around WO3 and NiO joined by a patented adhesive polymer electrolyte with transparent conductors of ITO (In2O3:Sn).
	Conver Light™ Double glass	1.1	0.59-0.15		0.43-0.13	
	Conver Light™ Triple glass	0.6	0.54-0.14		0.36-0.10	
IP Glass Technology B.V., 159 Groenendaal, NL-3011 SR Rotterdam NETHERLANDS. Tel.: +31 10 213 67 52. fax: +31 10 213 17 09. info@intraprojects.com. www.intraprojects.com 	ECD Glass		0.62–0.035		0.48–0.09	[Accessed 24.06.2014]. Electrochromic Glass in cooperation with SAGE Electrochromics. 10 years warranty. WO3-based. Passed ASTM E-2141-06. Switching time: 3-5 min, Durability: 100 000 cycles, 30 years, Electrical demand: <5 VDC, Max size: 107x150 cm
GENTEX Corporation, 600 North Centennial Street, Zeeland, MI 49464, USA. Tel.: +1 616 772 1800. fax: +1 616 772 7348. www.gentex.com  	Gentex Auto-Dimming					[Accessed 24.06.2014]. Electrochromic mirrors for automotive applications.
	Aircraft windows					

3 Building energy performance simulations

To investigate the energy saving potential of adaptable and controllable smart windows, selected commercial products and theoretical cases have been simulated in the software package IDA ICE (EQUA Simulation AB, 2018g). This process will be presented in the following subchapters.

3.1 Building modelling

3.1.1 Building envelope

The building geometry and material specifications for this work are based on the BESTEST case 600 from the ANSI/ASHRAE standard 140-2017 - *Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs (Ashrae, 2017).* Note that only selected inputs are taken from BESTEST case 600 and other building settings will be explained in later chapters.

The geometry and material specifications from BESTEST case 600 represents a low mass building with two windows facing south with a window-to-wall ratio of 55 %. See Fig.1 for an illustration of how the model is represented in IDA ICE and Fig.2 for the associated dimensions.

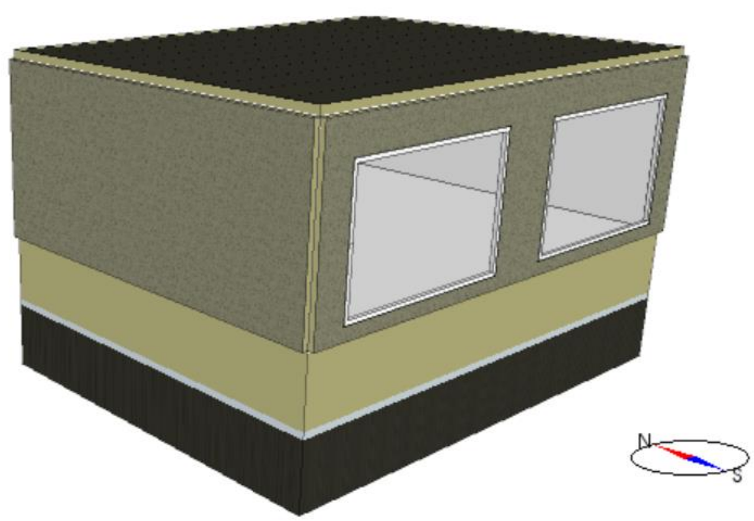


Fig.1. 3D building model in IDA ICE (EQUA Simulation AB, 2018a). External walls and roof with two windows facing south.

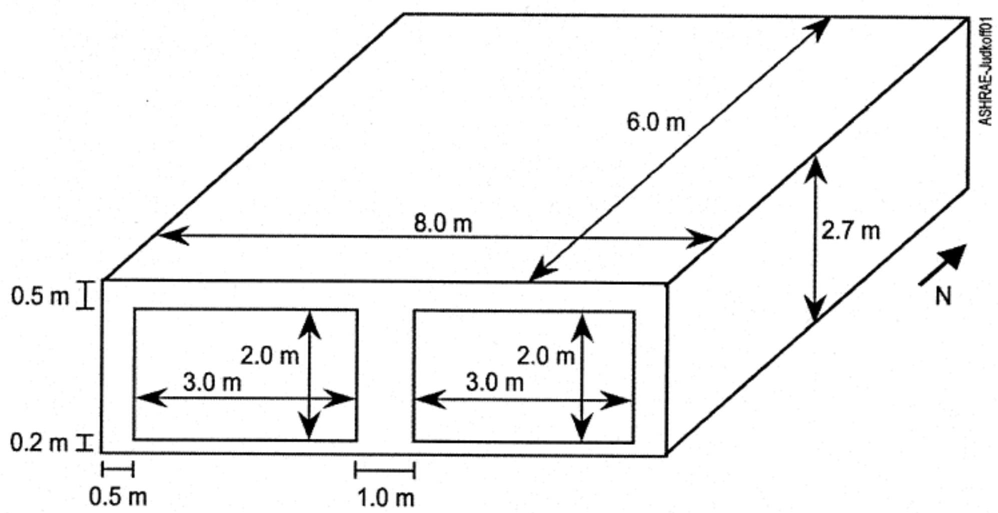


Fig.2. Building geometry based on BESTEST Case 600 (Ashrae, 2017).

All building surfaces are considered external and the floor is connected to the ground. The ground model is calculated in IDA ICE according to ISO 13370 (International Organization for Standardization, 2017). There are no nearby shading objects, so the building will continuously be exposed to solar radiation from dawn to sunset. The building consists of a single thermal zone and all geometry, material specifications and other settings are equal for every simulated window technology and location. See Table 4 for a detailed presentation of each building component and the associated layers.

Table 4. Material specifications BESTEST case 600 - Low mass building.

Material Specifications BESTEST Case 600 - Low mass building						
Layer	**k (W/(mK))**	**Thickness (m)**	**U-value (W/(m^2K))**	**R-value (m^2K/W)**	**Density (kg/m^3)**	**Cp (J/(kgK))**
			Exterior Wall (inside to outdoors)			
Interior surface coefficient	-	-	8.29	0.12	-	-
Plasterboard	0.16	0.012	13.33	0.08	950	840
Fiberglass quilt	0.04	0.066	0.61	1.65	12	840
Wood siding	0.14	0.009	15.56	0.06	530	900
Exterior surface coefficient	-	-	29.30	0.03	-	-
Total air-air			**0.51**	**1.94**		
			Floor (inside to outdoors)			
Interior surface coefficient	-	-	8.29	0.12	-	-
Timber flooring	0.14	0.025	5.60	0.18	650	1200
Insulation	0.04	1.003	0.04	25.08	0.0001[1]	0.0001[1]
Total air-air			**0.04[2]**	**25.38**		
			Roof (inside to outdoors)			
Interior surface coefficient			8.29	0.12		
Plasterboard	0.16	0.010	16.00	0.06	950	840
Fiberglass quilt	0.04	0.112	0.36	2.79	12	840
Roofdeck	0.14	0.019	7.37	0.14	530	900
Exterior surface coefficient	-	-	29.30	0.03	-	-
Total air-air			**0.32**	**3.15**		

Summary - Input report from IDA ICE

Building component	**Area (m^2)**	**U-value (W/(m^2K))**	**U*A (W/K)**
Walls	63	0.51	32
Floor	47	0.03[2]	2
Roof	47	0.32	15
Windows	12	N/A[3]	N/A[3]
Total	**170**	**N/A[3]**	**N/A[3]**

Volume	**Window-to-wall**	**Window-to-envelope**	**Envelope area per volume**
128 m^3	55 %	7 %	1.33 m^2/m^3

[1] The underfloor insulation has a minimum density and specific heat capacity as according to ashrae standard 140-2017.

[2] Total air-to-air floor U-value does not match to the input report from IDA ICE due to that the software takes into consideration the ground properties in the calculations of the U-value according to ISO 13370.

[3] Non-applicable. Window properties will vary from each case, hence will also the heat transfer coefficient and total values vary from each case.

Note here that the U-value from the IDA ICE input report for the floor is deviating from the BESTEST case 600 inputs. This is due to that the software takes into consideration the ground properties in the calculations (EQUA Simulation AB, 2018e). This is however a relative small deviation and will be the same for all simulated cases.

3.1.2 Climate and location

To investigate how the various technologies perform in different climates, three separate locations have been chosen based on their latitude, i.e. Trondheim (Norway), Madrid (Spain) and Nairobi (Kenya). Each location has an associated climate data file based on statistically determined hot or cold days, used for sizing of cooling or heating loads, called typical meteorological year (TMY). The files are derived from Integrated Surface Hourly (ISH) weather data originally archived at the National Climatic Data Center (EQUA Simulation AB, 2018b). These are gathered from ASHRAE IWEC2 database, which has been documented in ASHRAE Fundamentals 2013 (EQUA Simulation AB, 2018c). Each climate file represents the airport in the respective city. See Table 5 for a presentation of the locations.

Table 5. Geographical information of the chosen locations. Table shows latitude, longitude, elevation and time-zone for each city and country.

City and Country	Latitude (°)	Longitude (°)	Elevation (m)	Time zone (h)
Trondheim, Norway	63.47 N	10.93 E	17	1.0 E
Madrid, Spain	40.45 N	3.55 W	582	1.0 E
Nairobi, Kenya	1.32 S	36.92 E	1624	3.0 E

Each climate file contains hourly mean values of dry-bulb temperature, relative humidity, direct normal radiation, diffuse radiation on horizontal surface, windspeed (x- and y-direction) and cloudness. However, the most important variables for this work are the direct normal radiation, diffuse radiation on horizontal surface, dry-bulb temperature and the cloudness, which will be presented in more detail. Figure 3 shows the direct normal radiation, Fig.4 shows the diffuse radiation on horizontal surface, Fig.5 shows the dry-bulb temperature and Fig.6 shows the cloudness for Trondheim, Madrid and Nairobi for an entire year, respectively. In Table 6 all variables are presented for all three locations.

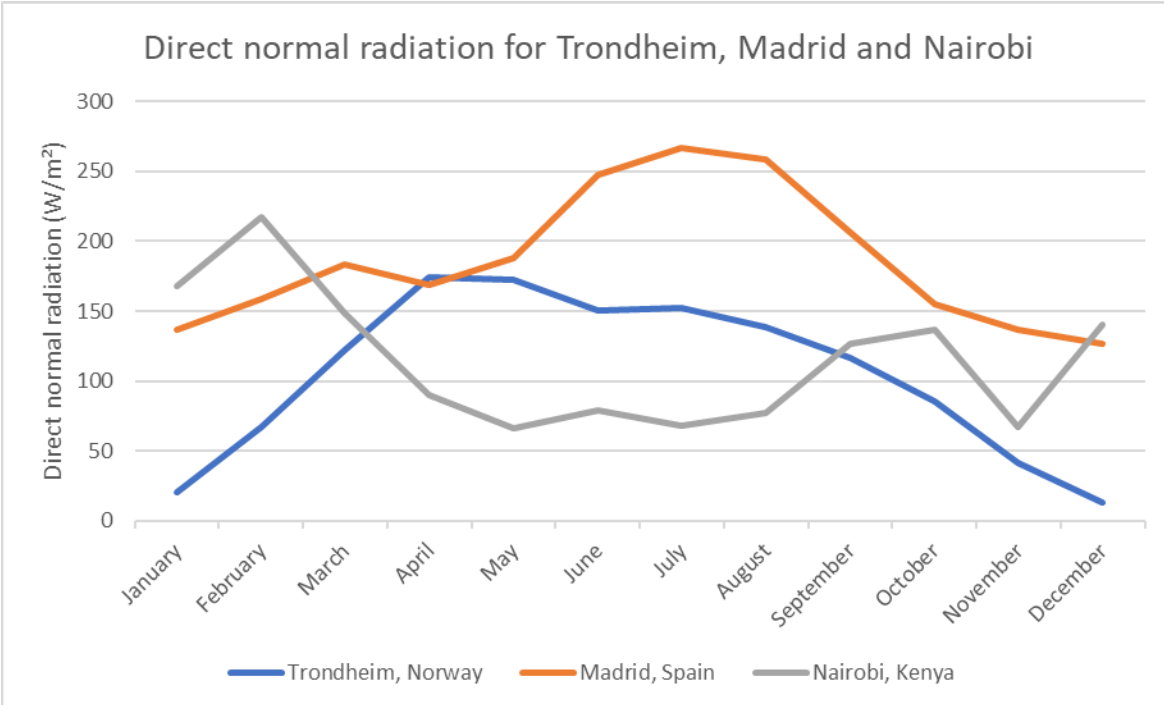


Fig.3. Direct normal radiation as a function of time for Trondheim, Madrid and Nairobi.

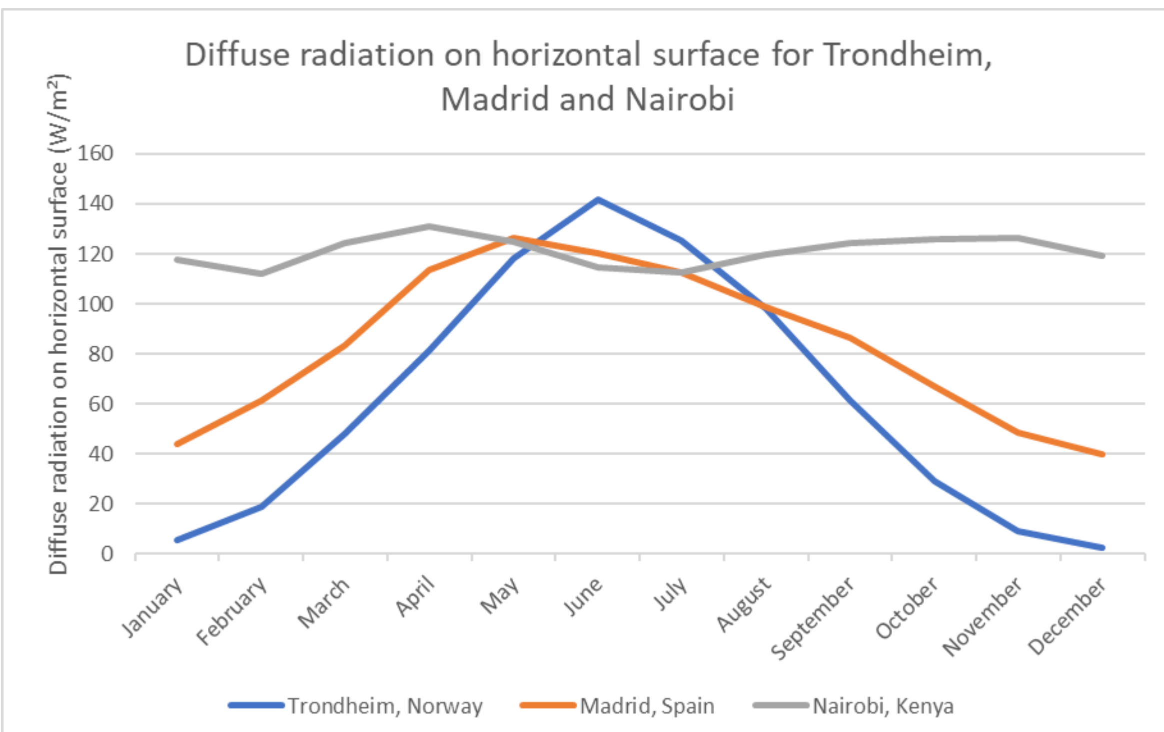


Fig.4. Diffuse radiation on horizontal surface as a function of time for Trondheim, Madrid and Nairobi.

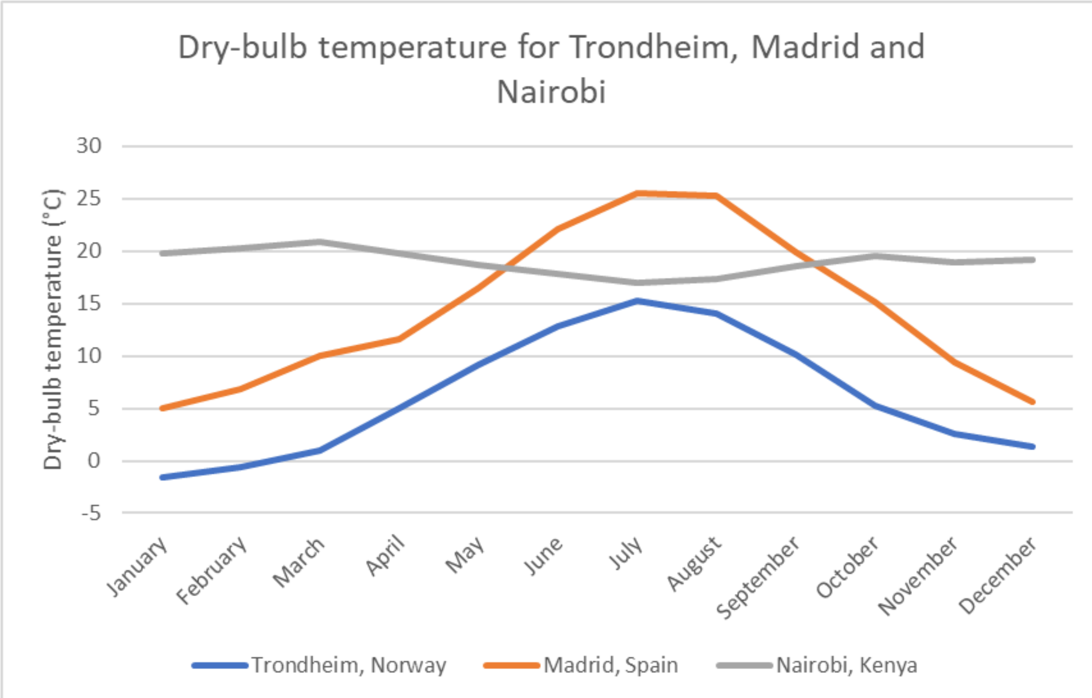


Fig.5. Dry-bulb temperature as a function of time for Trondheim, Madrid and Nairobi.

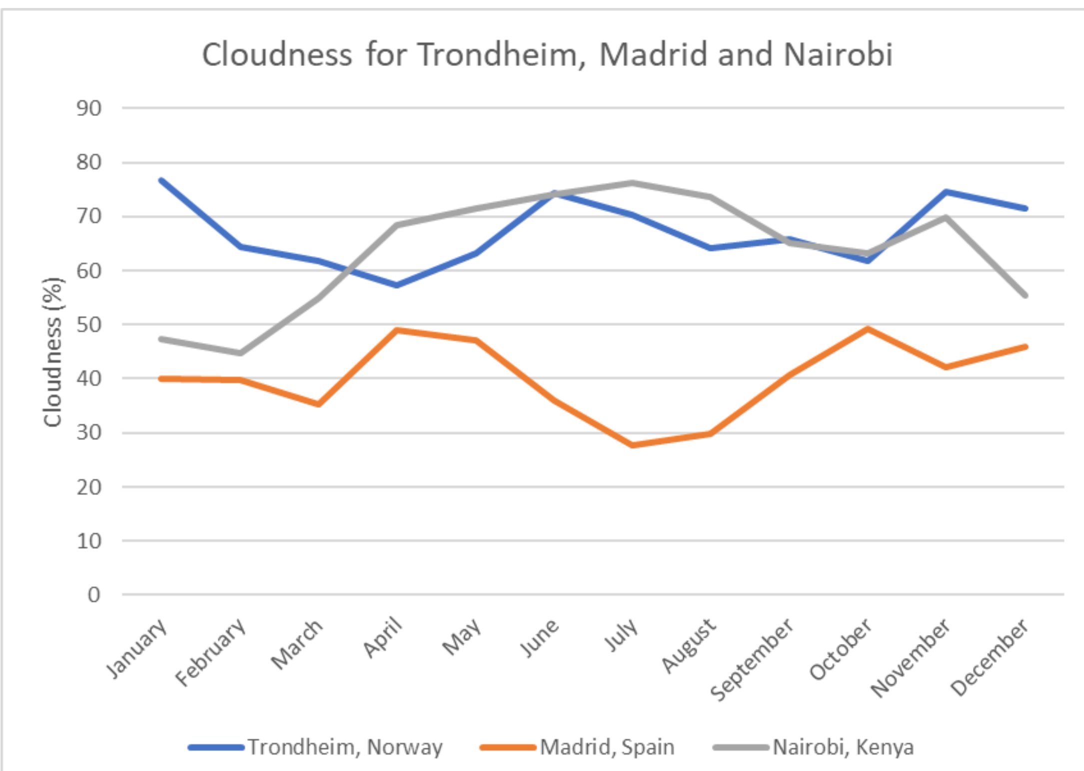


Fig.6. Cloudness as a function of time for Trondheim, Madrid and Nairobi.

Table 6. Climate data for Trondheim, Madrid and Nairobi. Table shows monthly values for dry-bulb temperature, direct normal radiation, diffuse radiation on horizontal surface and cloudness.

	Dry-bulb temperature (°C)			Direct normal radiation (W/m²)			Diffuse radiation on horizontal surface (W/m²)			Cloudness (%)		
Month	Trondheim, Norway	Madrid, Spain	Nairobi, Kenya	Trondheim, Norway	Madrid, Spain	Nairobi, Kenya	Trondheim, Norway	Madrid, Spain	Nairobi, Kenya	Trondheim, Norway	Madrid, Spain	Nairobi, Kenya
January	-2	5	20	21	136	168	6	44	118	77	40	47
February	-1	7	20	67	159	218	19	61	112	64	40	45
March	1	10	21	122	184	148	48	84	124	62	35	55
April	5	12	20	175	169	90	81	114	131	57	49	68
May	9	17	19	172	188	66	118	127	125	63	47	72
June	13	22	18	150	248	79	142	121	115	74	36	74
July	15	26	17	153	267	68	125	113	113	70	28	76
August	14	25	17	138	259	77	98	99	120	64	30	74
September	10	20	19	117	206	127	61	86	124	66	41	65
October	5	15	20	86	155	137	29	67	126	62	49	63
November	3	9	19	42	136	67	9	48	127	75	42	70
December	1	6	19	13	126	140	2	40	119	72	46	55
Mean	6	15	19	105	186	115	62	84	121	67	40	64
Min	-2	5	17	13	126	66	2	40	112	57	28	45
Max	15	26	21	175	267	218	142	127	131	77	49	76

3.1.3 Internal gains and setpoints

Internal gains are modelled as an office building and consist of occupants, equipment and lighting. The number of occupants is set to one person that is present 07-17 during weekdays. Activity level is set to 1 MET (reading, seated) with a constant CLO 0.85 ± 0.25, both are calculated according to the Fanger's model for thermal comfort (EQUA Simulation AB, 2018d). The equipment emits 150 W and is also set to be active only during occupant hours. All energy from equipment is deposited in the zone as thermal energy. The lighting has an input of 50 W with a luminous effect of 12 lm/W and is located in the center of the zone. Lighting is also set to be active only during occupant hours 07-17 on weekdays, where it is controlled by user-defined setpoints, i.e. max power when daylight is below 100 lux and is turned off when it reaches 500 lux. For values between 100-500 lux the software linearly interpolates so that the lighting gradually increases the lighting power as natural daylight decreases. Total internal gains are 200 W according to BESTEST case 600 (Ashrae, 2017).

Thermal setpoints for the thermal zone are set to 21°C for heating and 25°C for cooling, which are default settings in IDA ICE, and are associated with the mean air temperature. The software also categorizes each heat flux entering or leaving the zone into "during cooling", "during heating" and “rest of time”. When the zone temperature is above or slightly below the cooling setpoint, all heat fluxes are collected in “during cooling”. Similar, all heat fluxes are collected in “during heating” when the zone temperature is below or slightly above the heating setpoint. “Slightly” mean in both cases 1°C which is the default setting in IDA ICE. When the zone temperature is in between, i.e. 22 - 24°C, the heat fluxes are collected in “rest of time”.

3.1.4 Heating and cooling

The modelling of the heating and cooling of the building is done in IDA ICE by so called ideal heaters and coolers. These have no physical representation in the model and are set to 10 000 W each such that they always will be able to meet the heating and cooling demands to obtain the setpoints for the zone. The coefficient of performance (COP) is set equal to 1 for both heating and cooling, which means that they are 100 % efficient. No air handling unit (AHU) is connected to the building and heating for domestic hot water is not considered in the model. All energy delivered to the building are electric energy and no distribution losses are accounted for. Also, there are no losses due to thermal bridges, infiltration or other system losses. These factors are of no interest in this study and makes the comparison of each case easier.

3.2 Smart window modelling

Since building performance simulation (BPS) tools were not originally developed for smart windows, simulating the performance can be significantly more complex than for conventional static windows (Favoino et al., 2017). Loonen et al. (2017) investigated the capabilities of five widely used BPS tools in terms of their ability to model energy and occupant performance of adaptive facades. Here, it was concluded that IDA ICE has the capability to model smart windows by the use of custom made control macros. However, it requires a higher level of work and expertise from the user because a script for the control strategy needs to be manually developed (Favoino et al., 2017). When modelling and simulating smart windows, three important aspects considering the different technologies can be summarized as followed (Favoino et al., 2017):

1. Control mechanism. The controllable windows (referred to as extrinsic), i.e. ECW, which responds to an external signal, and the adaptable (referred to as intrinsic), i.e. TCW and PCW, which responds to changing boundary conditions.
2. Wavelength range. The smart windows can change their optical properties, as they tint, differently in the whole spectrum.
3. Optical properties. Depending on the refractive index of the materials embedded in the functional layer, the smart window could have a diffuse behavior when activated.

IDA ICE is widely used in the architecture, engineering and construction (AEC) industry, especially in the northern European countries, for whole-building energy simulations and was chosen for this work based on its user flexibility and high transparency, offering the user to create own models and to log any variable or parameter (EQUA Simulation AB, 2018i). This was an important feature since the program does not contain any default model for smart window simulations. However, the software allows the user to model these by custom made algorithms for shading control. By logging relevant variables, the custom-made algorithms could be validated while running the simulations. The modelling of the smart windows is carried out by using the "standard window" model. Here, the various layers of the windows are not modelled in detail and it uses a fixed curve for the angle dependence and does not take into consideration the spectral dependency of the optical parameters (EQUA Simulation AB, 2018f). For the tinting of the smart windows, an integrated shading device is used to change the optical properties by multiplying the clear state values with the relevant multiplier. (EQUA Simulation AB, 2018f). Inside a zone, diffuse light is spread diffusely, while the exact target location of the direct beam is computed. After the first reflection on a zone surface, the direct beam is spread diffusely in the room. Here the whole surface that is hit is regarded to reflect with equal intensity, not just the lit portion of this surface (EQUA Simulation AB, 2018f). By using the "standard window" model and an integrated shading device, it is possible to model the behavior of a smart windows in a reasonable way.

3.2.1 Emulating the tinting of smart windows in IDA ICE

Two types of window models are available in IDA ICE, i.e. "standard window" and "detailed window". Since there is no built-in function for modelling smart windows in IDA ICE and the information concerning smart windows provided by the manufacturers are for entire window systems, these are modelled with the standard window model in this work. Here, the technical aspects of the smart windows are modelled by implementing an integrated shading device. The user inputs are the U-value, g-value, T_{sol} and T_{vis}. These are given for the clearest state of the smart windows. In IDA ICE, the solar spectrum for T_{sol} lies between 300-2500 nm while T_{vis} is ranging between 380-780 nm (the visual spectrum). The input for the integrated shading device is given as multipliers for the U-value, g -value and T_{sol}. The multiplier for the U-value is set to 1 since it does not change with various tinting states. The multipliers for the g-value and T_{sol} are obtained by the following equation:

$$m_g = \frac{g_{darkest\ state}}{g_{clearest\ state}} \quad (1)$$

where

- m_g is the multiplier for the g-value ranging between 0 and 1.
- $g_{darkest\ state}$ is the g-value at the darkest state of the smart window (-).
- $g_{clearest\ state}$ is the g-value at the clearest state of the smart window (-).

Note that Eq.1 presents the calculations for the multiplier for the g-value, but the same calculation is also valid for the multiplier for T_{sol}.

Together with the actual shading signal, the optical properties of the tinted smart window at any shading state are calculated by the following equation:

$$\text{g–value} = \left(m_g * g_{clearest\ state}\right) * s + g_{clearest\ state} * (1 - s) \tag{2}$$

where

- g-value is the value of the tinted window at a given shading signal (-).
- m_g is the multiplier for the g-value ranging between 0 and 1.
- $g_{clearest\ state}$ is the g-value at the clearest state of the smart window (-).
- s is the shading signal ranging between 0 and 1, where 0 is equal to no shading and 1 is equal to full shading.

Note that Eq.2 presents the calculations for the g-value, but the same calculation is also valid for $T_{sol.}$

3.2.2 Assumptions and limitations

Due to that IDA ICE does not currently have a default function for smart windows, the standard window model with an integrated shading device has been used. The smart windows are controlled by custom made algorithms that have not been validated with an actual case of other simulation programs so there may be deviations accordingly. The following assumptions and simplifications have been made:

- Energy consumption by the ECW is not accounted for in the simulations. This energy consumption is however low, and it is assumed that power is only required to tint the window and not to maintain a certain tinting level. Some ECW may need power to maintain a certain tinting level.

- The control strategies are not optimized considering controller setpoints/thresholds or control levels for the different technologies. Further, the control strategies are not adapted to fit a certain climate/location.
- From previous work made by (Mäkitalo) it was shown that the tinting speed of the ECW had negligible effect on the energy results, hence a PI-controller could be used for the operative temperature and daylight control algorithms. This avoids oscillations, which could occur when smart windows are controlled based on the same variables that is affected by the tinting. This makes the simulations more robust.

A limitation to this study, that has not been mentioned in previous work by Reynisson (2015) or Mäkitalo (2013), is the issue concerning T_{vis}. The fact that IDA ICE does not have a default function for handling smart windows when using the standard window model, mean that it cannot take into consideration the spectral dependency when a smart window tint, as was stated as an important aspect concerning smart windows by Favoino et al. (2017). The integrated shading device in IDA ICE does not have the input option of a multiplier for T_{vis} and is designed so that the visual spectrum will be decreased with the same factor (multiplier) as the whole solar spectrum. This mean that the software does not take into account that the optical properties of the smart windows vary depending on wavelength. This is an important aspect of smart windows, as they can modulate the thermo-optical properties in the whole solar spectrum, or only in the visible part, non-visible part or independently in both parts of the solar spectrum (DeForest et al., 2017), where the intention is to reject the heat from solar radiation while still allow for natural daylight. The software instead uses a fixed parameter called VISGAIN which is calculated by the following equation:

$$VISGAIN = \frac{T_{vis}}{T_{sol}} \tag{3}$$

where T_{vis} and T_{sol} are the input data for the smart window in its clearest state. This is further used to calculate the daylight level (lux) at a user defined workplane and will have an effect on the following cases:

- ECW - “real cases” and “real cases with same U-value”
- TCW - “real cases” and “real cases with same U-value”

The following will be affected considering the simulations:

- Artificial lighting is controlled by the daylighting setpoints, which mean that the energy consumption will have deviations from actual values for both the ECW and TCW.
- The ECW controlled by daylight is set to maintain a daylight level at 500 lux at a user defined workplane. This daylight level will have deviations from the “real” daylight level the workplane would have had if the ECW was able to change the optical parameters independently. This will further have an indirect impact on the energy consumption.

The deviation from the “real” value of the T_{vis} values will vary depending on the shading signal with the largest deviation of 43 % (0.001) at the darkest state for the ECW and 50 % (0.04) at the darkest state for the TCW. All other cases have the same multiplier for T_{vis} and T_{sol}, which mean they will not be affected by this due to that they change the optical parameters equally in both the visible spectrum as for the whole solar spectrum. In general however, the energy calculations are not affected since they are only determined by the g-value and T_{sol} in IDA ICE.

Smart windows can be simulated using various BPS tools available on the market. However, since these tools were not originally developed for switching façade elements such as smart windows, there are some limitations. By the study of Favoino et al. (2017), following limitations have been identified and should be considered during the simulations and when analyzing the results:

- Switchable window coatings have special angular-dependent optical properties that are different from regular specular glazing systems. In IDA ICE the window is modelled as a normal window which uses a fixed curve for the angle dependence .
- Some switchable window technologies, especially thermochromic materials have a hysteric dependence of optical properties on temperature. This mean that the window pane might

experience variations of temperatures, hence the tinting may vary across the window pane. This effect could have a significant impact on the windows energy performance and may also have significant impact on thermal and visual comfort. This hysteric effect is however not possible to take into account in any simulation tool.

Other limitations that should be considered are:

- In the TCW and the PCW, the active layer is often located in between the two outermost windows panes. In the IDA ICE however, the modelling of the measurements of temperature (°C) and solar radiation (W/m^2) are made on the outermost surface on the window pane. This may result in a deviation from how a "real case" TCW and PCW would tint by responding to temperature and solar radiation variations, respectively.
- No information about the U-value and T_{sol} for the PCW was provided by the manufacturer, instead both parameters use the input values for the TCW.
- No information was given about the solar radiation control levels for the PCW. Here, the chosen values are 100 W/m^2, which is by default settings in IDA ICE, for the clearest state and 450 W/m^2 for the darkest state, which was found in a study by Reinhart and Voss (2003) to be when occupants wanted to have their blinds drawn.

3.3 Smart window control strategies

Smart windows have the ability to change the optical parameters as a response to boundary conditions. The adaptable smart windows (TCW and PCW) change the parameters based on temperature (°C) and solar radiation (W/m^2), respectively, while the controllable windows (ECW) have the ability to change the parameters based on user preferences by applying a certain voltage to the window. Following chapters covers the cases selected for the simulations and associated control strategies.

3.3.1 Simulated cases

As mentioned earlier, information about real commercial smart window products has been collected from manufacturers and compiled into a table. From this table, one window from each technology (ECW, TCW and PCW) has been chosen to be simulated at each location (Trondheim, Madrid and Nairobi). Note that no information about the U-value and T_{sol} for the PCW was provided by the manufacturer, so as a solution the same values as for the TCW have been used. The same windows have also been simulated using the same U-values. In addition, two theoretical cases have been simulated where the optical properties take on fictitious values. These will further be noted as "Range 10-90" and "Range 0-100". Range 10-90 mean that T_{vis}, T_{sol} and g-value are set to 0.1 in the darkest state and 0.9 in the clearest state. Range 0-100 mean that T_{vis}, T_{sol} and g-value are set to 0 in the darkest state and 1 in the clearest state. Note here that the values for T_{sol} are not set to 1 or 0.9 for the range 0-100 and range 10-90, respectively. This is due to that IDA ICE does not allow for a T_{sol} -value that is equal or larger than the g-value. Instead, T_{sol} is set to be slightly lower than the g-value. Also, the software does not allow for values equal to 0. Here, the minimum value is set to 0.0001. See Table 7 for a presentation of each simulated case and associated control strategy and control levels. The frame fraction of the total window area is set to 10 % with a U-value of 2 W/(m²K) which is default settings in IDA ICE. The internal and external emissivity is set to 0.837 for all windows, also by default in IDA ICE. These settings are identical for each simulated case. A total of 63 simulations have been conducted during the period 1st of January 2018 to 31st of December 2018. Note that the climate data is associated with typical meteorological year (TMY) and does not correspond to the actual year of 2018. Each window technology and associated control strategy has been validated by logging relevant variables during a simulation and will be presented in the following chapters.

Table 7. All simulated cases for TCW, PCW and ECW. The table shows the various properties and associated control strategy and control levels for each simulated case.

		Case	Manufacturer	Product	U_g ($W/(m^2K)$)	T_{vis} (-)	T_{sol} (-)	g-value (-)	Control levels
Real cases	Adaptive	TCW	Pleotint LLC	Solarblue	1.36	0.38-0.08	0.16-0.05	0.27-0.14	clearest = 10°C, darkest = 65°C
		PCW	Chameleon	Chameleon 53	1.36[1]	0.52-0.42	0.16-0.05[1]	0.40-0.36	clearest = 100 W/m^2, darkest = 450 W/m^2
	Controllable	ECW - Sun	SAGE Electrochromics	Cool View Blue	1.59	0.40-0.023	0.30-0.01	0.46-0.09	Threshold = 450 W/m^2
		ECW - Operative temperature	SAGE Electrochromics	Cool View Blue	1.59	0.40-0.023	0.30-0.01	0.46-0.09	Threshold = 24 °C
		ECW - Daylight	SAGE Electrochromics	Cool View Blue	1.59	0.40-0.023	0.30-0.01	0.46-0.09	Threshold = 500 lux
Real cases with same U-value	Adaptive	TCW	Pleotint LLC	Solarblue	1.1	0.38-0.08	0.16-0.05	0.27-0.14	clearest = 10°C, darkest = 65°C
		PCW	Chameleon	Chameleon 53	1.1	0.52-0.42	0.16-0.05[1]	0.40-0.36	clearest = 100 W/m^2, darkest = 450 W/m^2
	Controllable	ECW - Sun	SAGE Electrochromics	Cool View Blue	1.1	0.40-0.023	0.30-0.01	0.46-0.09	Threshold = 450 W/m^2
		ECW - Operative temperature	SAGE Electrochromics	Cool View Blue	1.1	0.40-0.023	0.30-0.01	0.46-0.09	Threshold = 24 °C
		ECW - Daylight	SAGE Electrochromics	Cool View Blue	1.1	0.40-0.023	0.30-0.01	0.46-0.09	Threshold = 500 lux
Range 10-90	Adaptive	TCW	N/A[2]	N/A[2]	1.1	0.90-0.10	0.8999-0.10	0.90-0.10	clearest = 10°C, darkest = 65°C
		PCW	N/A[2]	N/A[2]	1.1	0.90-0.10	0.8999-0.10	0.90-0.10	clearest = 100 W/m^2, darkest = 450 W/m^2
	Controllable	ECW - Sun	N/A[2]	N/A[2]	1.1	0.90-0.10	0.8999-0.10	0.90-0.10	Threshold = 450 W/m^2
		ECW - Operative temperature	N/A[2]	N/A[2]	1.1	0.90-0.10	0.8999-0.10	0.90-0.10	Threshold = 24 °C
		ECW - Daylight	N/A[2]	N/A[2]	1.1	0.90-0.10	0.8999-0.10	0.90-0.10	Threshold = 500 lux
Range 0-100	Adaptive	TCW	N/A[2]	N/A[2]	1.1	1-0.0001	0.9999-0.00009999	1-0.0001	clearest = 10°C, darkest = 65°C
		PCW	N/A[2]	N/A[2]	1.1	1-0.0001	0.9999-0.00009999	1-0.0001	clearest = 100 W/m^2, darkest = 450 W/m^2
	Controllable	ECW - Sun	N/A[2]	N/A[2]	1.1	1-0.0001	0.9999-0.00009999	1-0.0001	Threshold = 450 W/m^2
		ECW - Operative temperature	N/A[2]	N/A[2]	1.1	1-0.0001	0.9999-0.00009999	1-0.0001	Threshold = 24 °C
		ECW - Daylight	N/A[2]	N/A[2]	1.1	1-0.0001	0.9999-0.00009999	1-0.0001	Threshold = 500 lux
		Reference window	Saint-Gobain	Cool-Lite 174+ar	1.1	0.69	0.38	0.41	N/A[3]

[1] Due to information missing from manufacturer, the U-value and Tsol value for PCW is the same as for TCW.
[2] Non-applicaple. Range 10-90 and Range 0-100 cases does not apply to any real product.
[3] Non -applicable. Reference window does not have any shading device and therefore no specified control strategy.

3.3.2 Thermochromic window control strategy

TCW are adaptable windows, which mean they adapt to a certain variable and cannot be controlled by an external force as for the ECW. The TCW changes its optical properties by responding to the temperature differences in the active layer in the window pane. The hotter the surface of the glass gets, the darker the glass will tint (InnovativeGlass, 2017). In IDA ICE this is modelled so that the user gives input-values of a minimum and maximum temperature (°C) for the clearest and darkest state of the window corresponding to the minimum and maximum shading signal (0-1). Temperature measurements are registered at the outer surface of the window. Here, the control levels are set to 10°C for the clearest state and 65°C for the darkest state (Suntuitive Self-tinting Glass, 2016). This is modelled in the advanced level in IDA ICE where the two models used are a "TQ multiplexer" and a "Proportional controller". The TQ multiplexer takes in both the heat flux and temperature, and then separates them into only temperature and heat flux links. Instead of using a linear function that could cause "corners" the proportional controller approximates real behavior with a sine function. This continuously changes the shading signal and hence the optical properties of the window as the temperature varies. The models are then connected to the windows' measurements and to the shading control. Figure 7 shows how the control strategy is modelled in IDA ICE. The control strategy has been validated by logging relevant variables during a simulation, see Fig.8 and Fig.9.

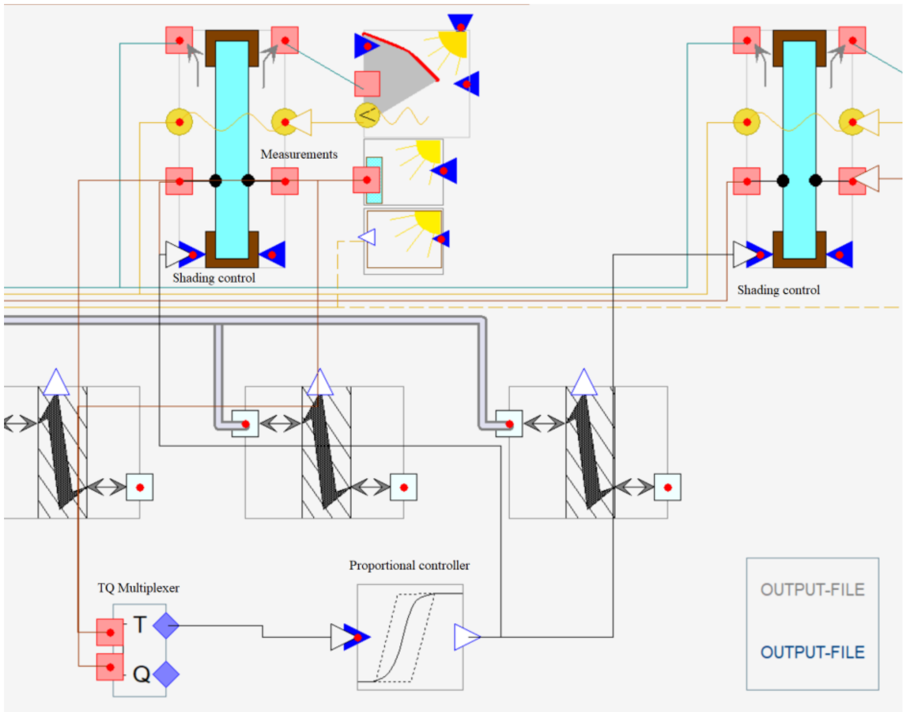


Fig.7. TCW control strategy macro model in IDA ICE. The control strategy is modelled in the advanced level.

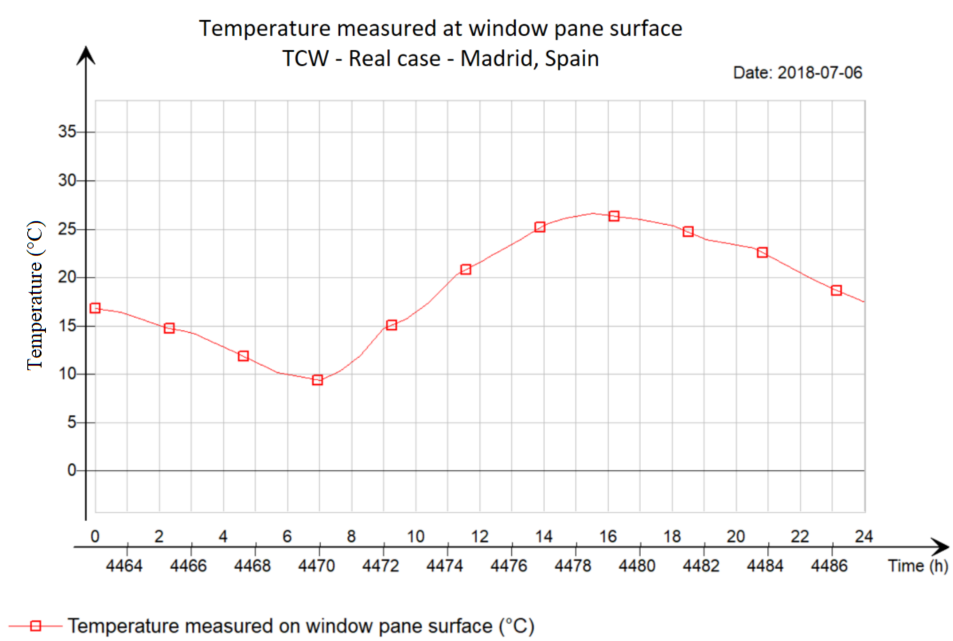


Fig.8. Temperature measured on window pane as a function of time. The diagram shows how the temperature on the window pane vary during a summer day in Madrid, Spain.

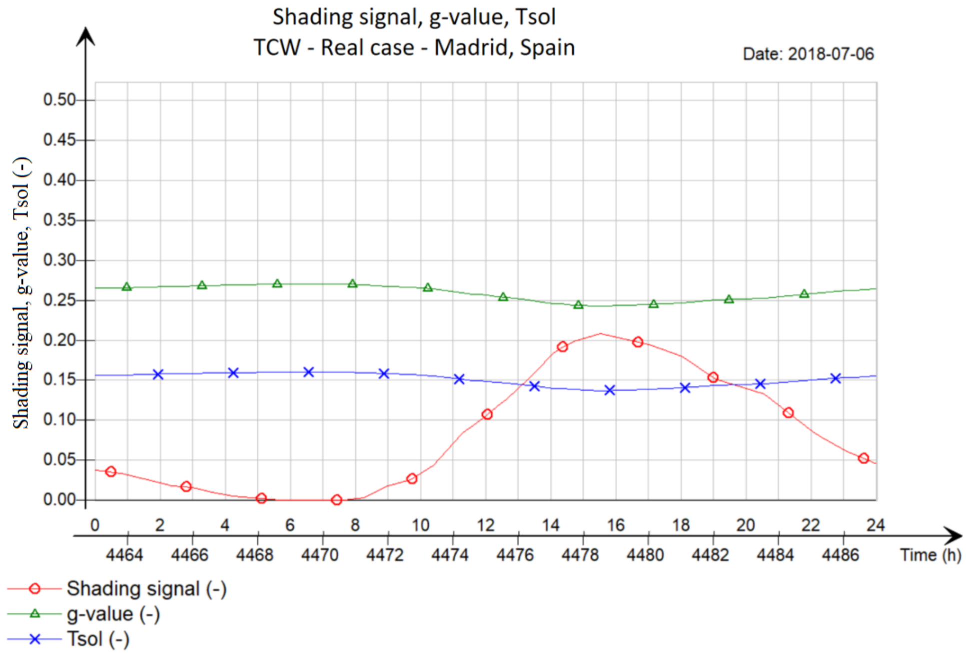


Fig.9. Shading signal, g-value and T_{sol} as a function of time. The diagram shows how the shading signal, g-value and T_{sol} vary during a summer day in Madrid, Spain.

3.3.3 Photochromic window control strategy

The PCW changes its optical properties by responding to the incoming global solar radiation (W/m^2) onto the active layer in the window pane. The more global solar radiation hitting the window pane, the darker the window tints. Depending on how the windows are manufactured the windows can have different configurations on the global solar radiation interval and can be customized to customer needs. In IDA ICE this is modelled so that the user gives minimum and maximum global solar radiation (W/m^2) values for the clearest and darkest state of the window corresponding to the minimum and maximum shading signal (0-1). Here the control levels are set to 100 W/m^2 for the clearest state and 450 W/m^2 for the darkest state. Note that no control levels were provided by the manufacturer so the control levels are set to the default setting in IDA ICE for the minimum threshold while the maximum threshold is based on the study by Reinhart and Voss (2003). The global solar radiation is a sum of the direct solar radiation (W/m^2) hitting the façade, diffuse solar radiation (W/m^2) coming from the sky and diffuse solar radiation (W/m^2) that is reflected from the ground. Also here a proportional controller is used to continuously change the shading signal and hence the optical properties of the window as the temperature varies. This is modelled in IDA ICE as a custom control macro for shading control and is composed by the models

“From façade”, “Adder” and “Proportional controller”. These are connected to each other and to the shading signal. Figure 10 shows how the control strategy is modelled in IDA ICE. The control strategy has been validated by logging relevant variables during a simulation, see Fig.11 and Fig.12.

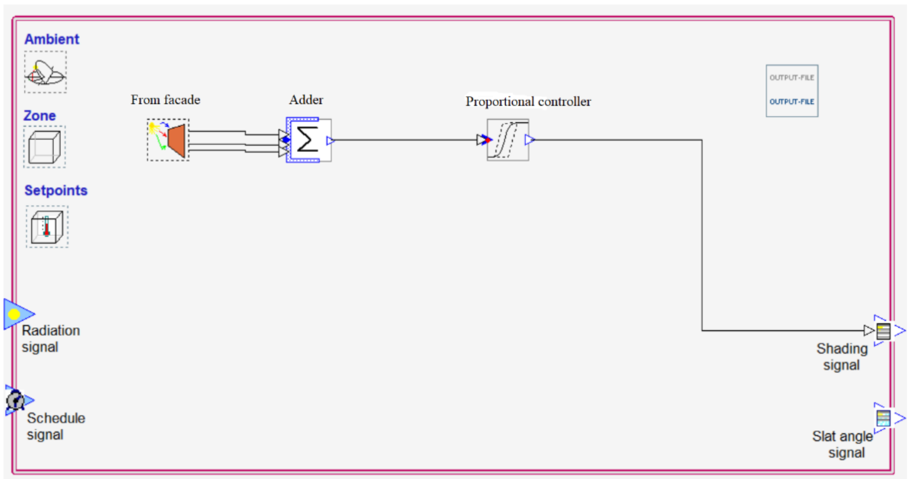


Fig.10. PCW control strategy macro model in IDA ICE. The control strategy is modelled in the simple window model by creating a new custom control macro for the integrated shading device.

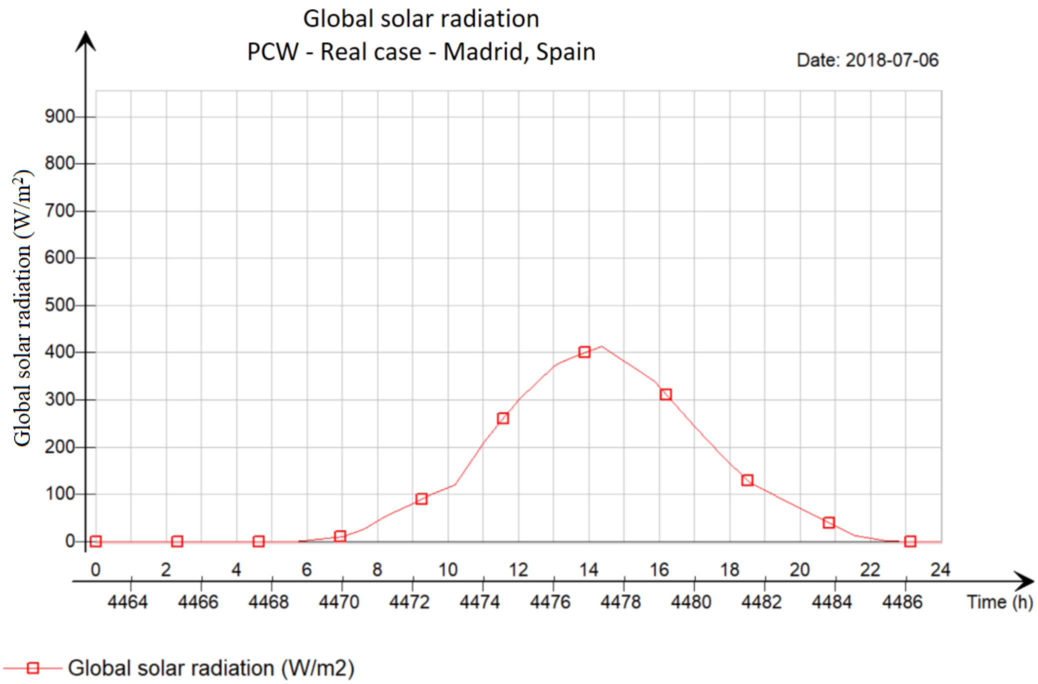


Fig.11. Global solar radiation as a function of time. The diagram shows how the global solar radiation vary during a summer day in Madrid, Spain.

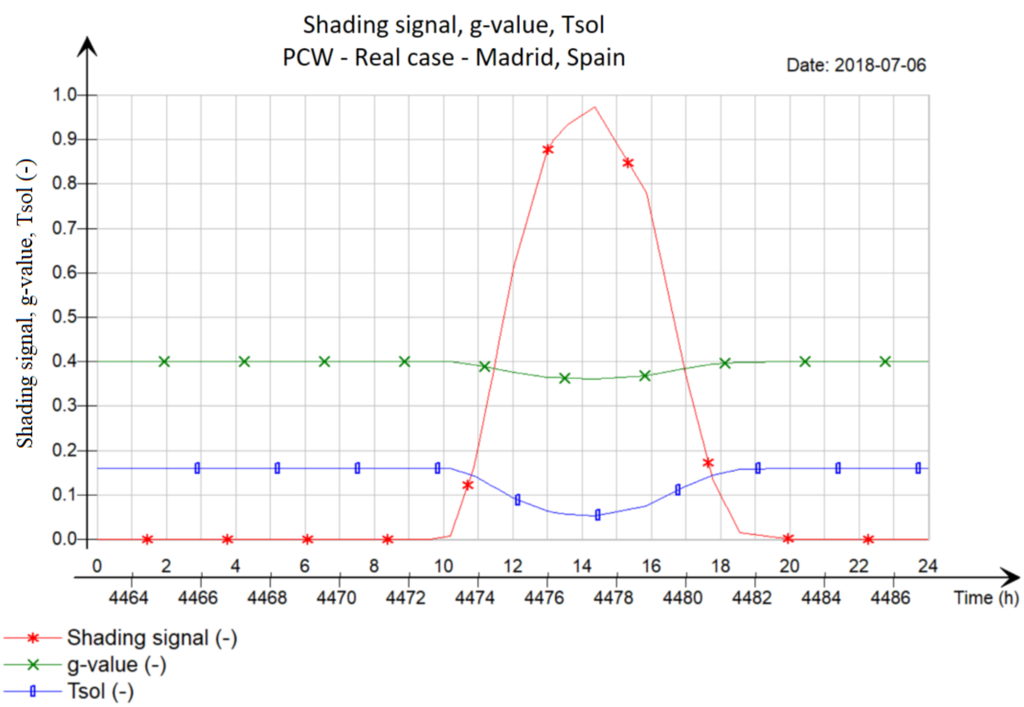


Fig.12. Shading signal, g-value, T_{sol} as a function of time. The diagram shows how the shading signal, g-value and T_{sol} vary during a summer day in Madrid, Spain.

3.3.4 Electrochromic window control strategy

While the adaptable TCW and PCW only respond to temperature and solar radiation, respectively, the ECW can basically be controlled in any desired way. In IDA ICE there are some predefined control strategies for shading controls built-in into the software. In addition to these, the program allows the user to create user-defined control macros for the integrated window shading device in the simple window model. As mentioned in the introduction, Mäkitalo (2013) and Reynisson (2015) investigated the possibilities for modelling complex control strategies for the ECW in IDA ICE. To limit the scope, the ECW are controlled by three different strategies based on operative temperature, indoor daylight and solar radiation, denoted “Operative temperature”, “Daylight” and “Sun”, respectively.

Sun control strategy

The Sun control strategy is predefined in IDA ICE and gives a shading signal equal to 1 when the global solar radiation entering the building through the window exceeds a user-defined threshold. Below this threshold the shading signal is equal to 0. This threshold is set to 450 W/m^2, which was found by a study by Reinhart and Voss (2003) to be the preferable level when occupants wanted to have their blinds drawn. The control strategy has been validated by logging relevant variables during a simulation, see Fig.13 and Fig.14.

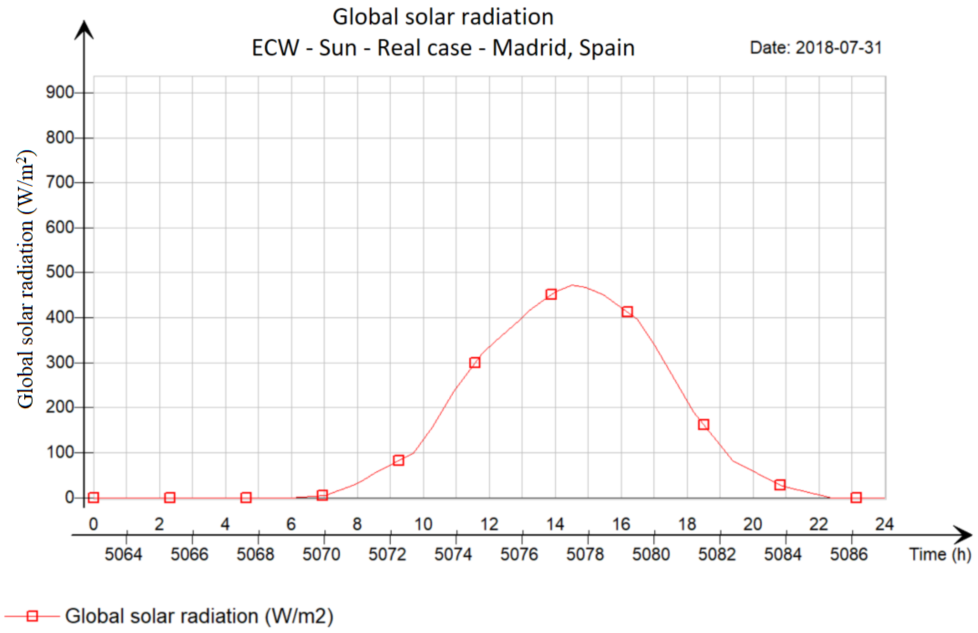


Fig.13. Global solar radiation as a function of time. The diagram shows how the Global solar radiation vary during a summer day in Madrid, Spain.

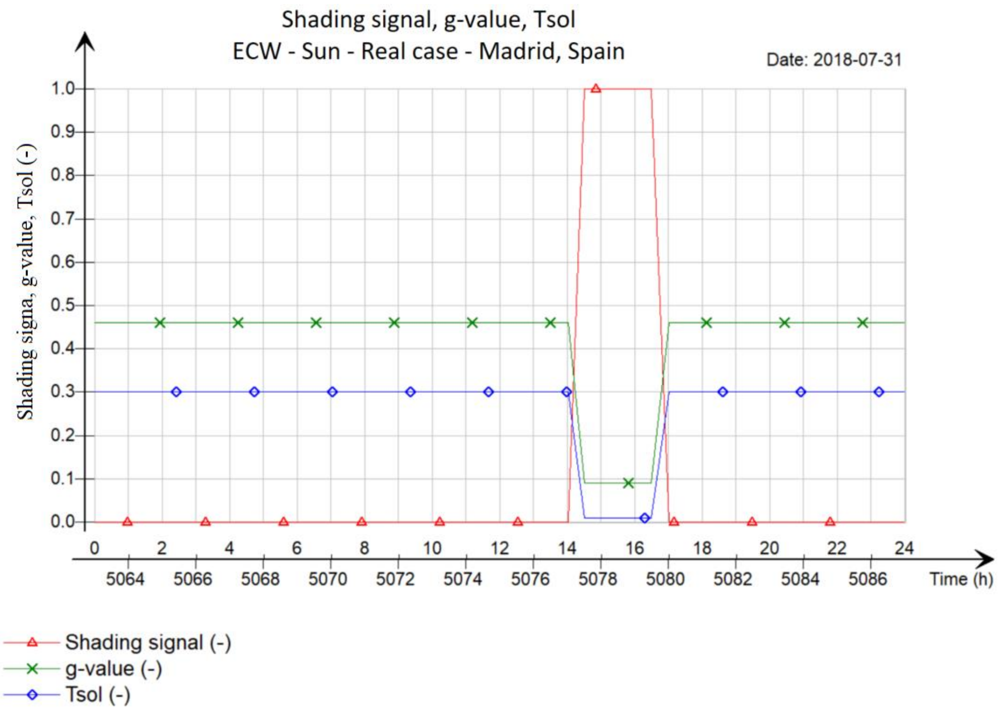


Fig.14. Shading signal, g-value and T_{sol} as a function of time. The diagram shows how the shading signal, g-value and T_{sol} vary during a summer day in Madrid, Spain.

Operative temperature control strategy

The Operative temperature control strategy was first created by Mäkitalo (2013) and controls the tinting level of the window by taking measurements of the operative temperature in the zone and comparing it to a user defined threshold. Here the threshold is set to 24°C (1°C bellow the cooling setpoint). When the measured operative temperature exceeds the user defined threshold the window dynamically tints to a darker state. It should be noted that the operative temperature is often higher than the air temperature during summer and lower during winter. This could lead to glare issues during winter when the sun is lower in the sky at the same time as the operative temperature for tinting the window is not high enough (Mäkitalo, 2013). Glare will however not be taken into consideration in this work. This is modelled in IDA ICE as a custom control macro for shading control and is composed by the models "From Zone", "inputs from Setpoints", "Add" and "PI-controller". These are connected to each other and to the shading signal. The PI-controller was shown by Mäkitalo (2013) to be more robust compared to an on-off controller. Since the tinting speed was shown to have little effect on the energy performance, this is an appropriate way to model the control strategy and to avoid oscillations. Figure 15 shows how the control strategy is modelled in IDA ICE. The control strategy has been validated by logging relevant variables during a simulation, see Fig.16 and Fig.17.

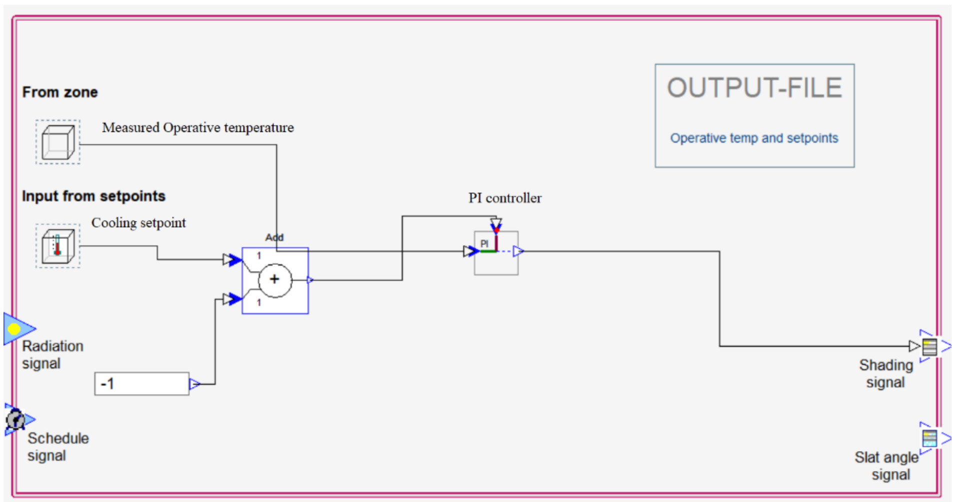


Fig.15. ECW - Operative temperature control strategy macro model in IDA ICE. The control strategy is modelled in the simple window model by creating a new custom control macro for the integrated shading device.

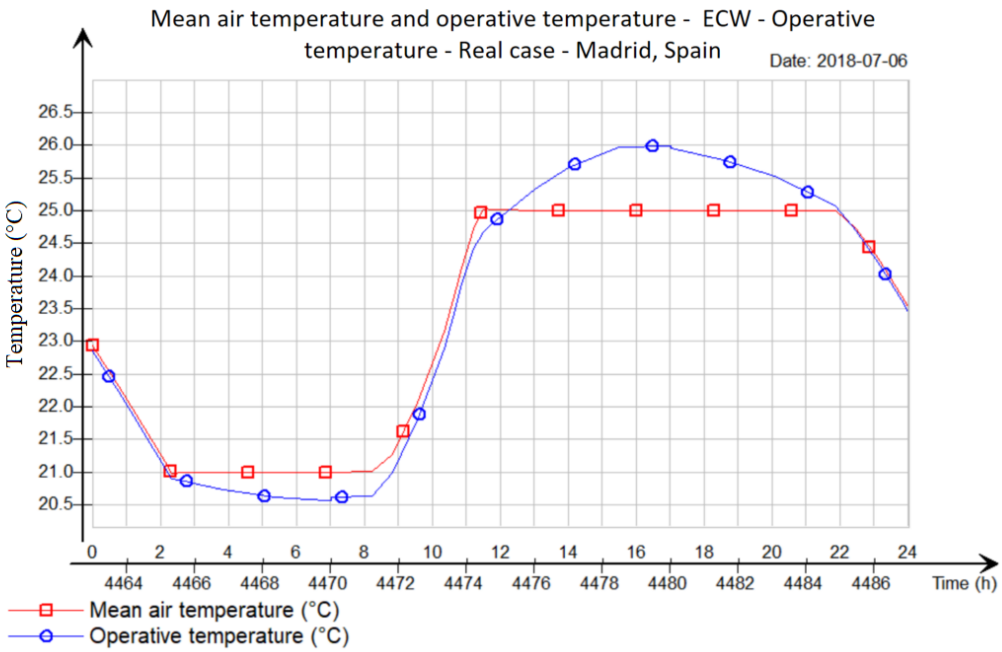


Fig.16. Mean air and operative temperatures as a function of time. The diagram shows how the mean air temperature and operative temperature inside the zone vary during a summer day in Madrid, Spain.

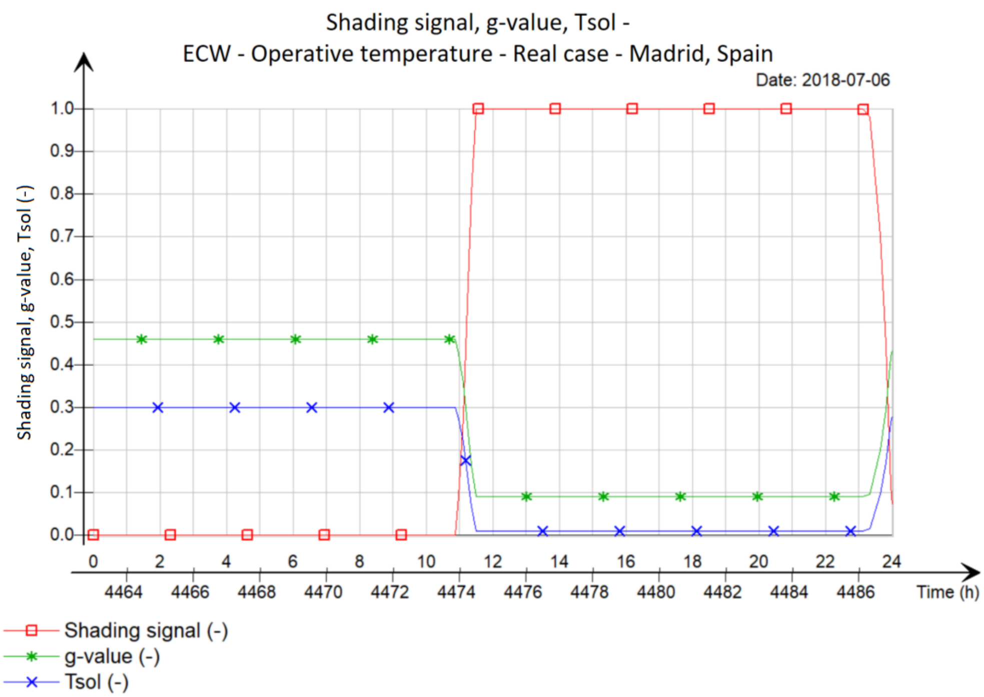


Fig.17. Shading signal, g-value and T_{sol} as a function of time. The diagram shows how the shading signal, g-value and T_{sol} vary during a summer day in Madrid, Spain.

Daylight control strategy

The Daylight control strategy was also created by Mäkitalo (2013) and controls the tinting level of the smart window by taking measurements of the lux level at a user defined workplane inside the zone and comparing it to a user defined threshold. Here the threshold is set to 500 lux corresponding to typical desk work for an office building (International Organization for Standardization, 2002). When the measured lux-level exceeds the user defined threshold, the window dynamically tints to a darker state. The workplane is positioned in the middle of the zone at a height of 0.6 m. This is modelled in IDA ICE as a custom control macro for shading control and is composed by the models "ZoneSensor" and "PI-controller". These are connected to each other and to the shading signal. The PI-controller was shown by Mäkitalo (2013) to be more robust compared to an on-off controller. Since the tinting speed was shown to have little effect on the energy performance, this is an appropriate way to model the control strategy and to avoid oscillations. Figure 18 shows how the control strategy is modelled in IDA ICE. The control strategy has been validated by logging relevant variables during a simulation, see Fig.19 and Fig.20. Here the control threshold for the daylight at the workplane is set to equal 500 lux. When the measured daylight exceeds this threshold, the shading starts to dynamically tint towards 1.

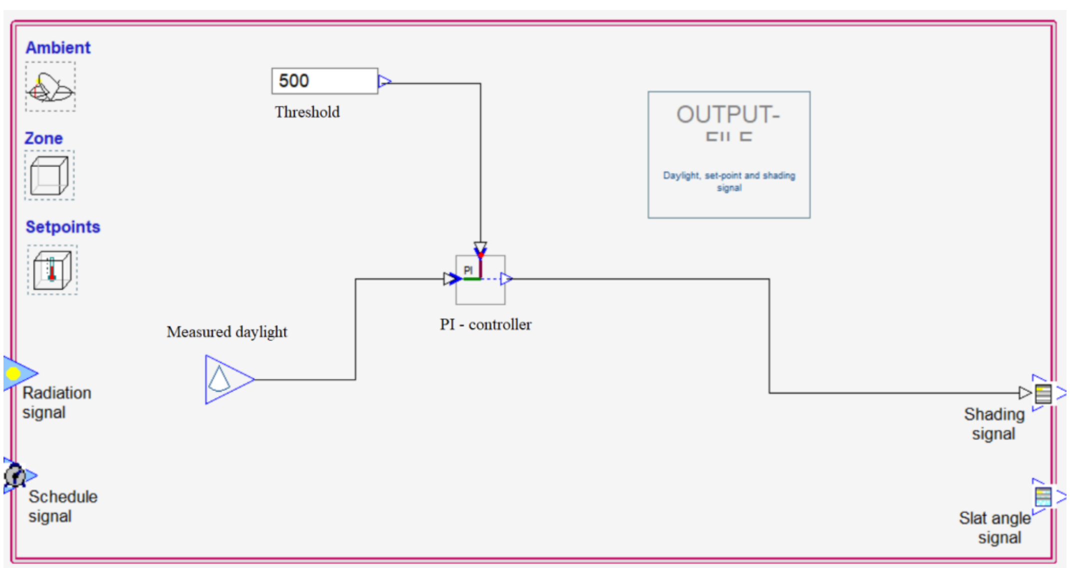


Fig.18. ECW Daylight control strategy macro model in IDA ICE. The control strategy is modelled in the simple window model by creating a new custom control macro for the integrated shading device.

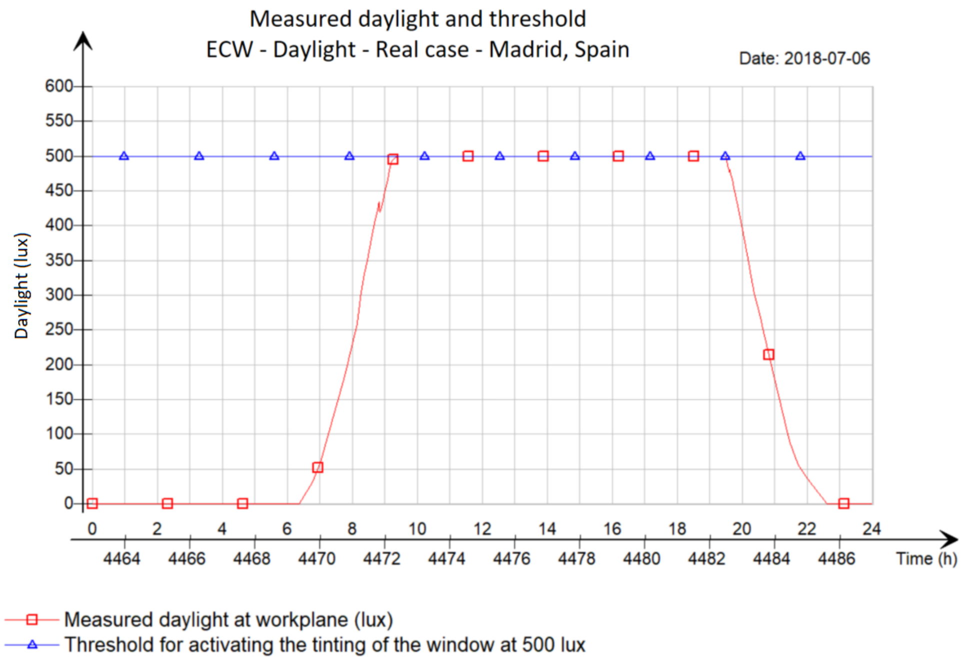


Fig.19. Measured daylight at workplane as a function of time. The diagram shows the threshold set to 500 lux and how the measured daylight vary during a summer day in Madrid, Spain.

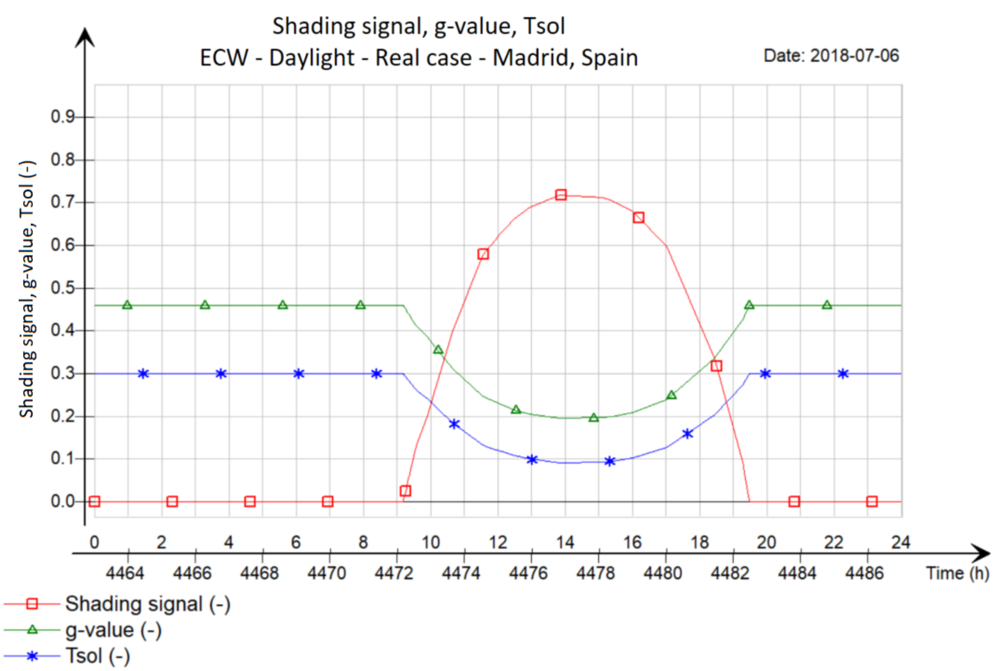


Fig.20. Shading signal, g-value and T_{sol} as a function of time. The diagram shows how the shading signal, g-value and T_{sol} vary during a summer day in Madrid, Spain.

4 Results

There are several different options concerning what results that can be obtained from simulations in IDA ICE such as delivered energy, peak loads and energy balances. In addition, the time dependent energy consumption of each energy carrier can be observed, and each variable can be logged. To thoroughly see the impact on energy consumption of smart windows the following results have been analyzed during the simulation period 1st of January 2018 to 31st of December 2018:

- Total delivered energy to the building divided into heating, cooling equipment and lighting (kWh/year).
- Monthly energy balances divided into building envelope transmission, window and solar, occupants, equipment, lighting, heating and cooling (kWh).
- Peak loads associated with heating, cooling and solar heat gain (W/m^2).
- Time dependent energy balances divided into building envelope transmission, window and solar, occupants, equipment, lighting, heating and cooling (W).
- Monthly and annual solar heat gain during cooling and heating hours (kWh).

Since this study is focusing on the impact of the smart windows on the energy consumption of a building, the solar heat gain through windows will also be presented in more detail. To limit the scope, the total delivered energy for each case will first be presented, followed by a more detailed presentation of the ECW controlled by operative temperature in comparison to the reference window. Visual and thermal comfort have not been considered when analyzing the results.

4.1 Total delivered energy - all simulated cases

Total delivered energy shows the total energy the building has consumed throughout an entire year simulation. For this work delivered energy is divided into heating, cooling, equipment and lighting. The following results are for an entire year simulation of all 63 simulated cases for Trondheim, Madrid and Nairobi. Comparisons are made to the reference window for each location which is set to 100 %. The results are first presented for all cases in Fig.21, and thereafter based on the location with associated tables. To get a picture of how the building in general performs for the different locations, following can be observed by comparing the reference windows for each location:

- Less total delivered energy is used by the building for locations further south, i.e. 6922 kWh/year in Trondheim, 6122 kWh/year in Madrid and 3419 kWh/year in Nairobi.
- Total energy demand is higher during the winter periods compared to the summer periods for all locations.
- The energy demand is shifting from a heating dominated demand to a cooling dominated demand for locations further south, i.e. from the total delivered energy, 18 % is due to cooling in Trondheim, 56 % is due to cooling in Madrid and 68 % is due to cooling in Nairobi.
- Less energy due to artificial lighting is required for locations further south, i.e. 24 kWh/year in Trondheim, 17 kWh/year in Madrid and 9 kWh/year in Nairobi.
- The various locations have no influence on the energy used by equipment, hence the energy demand is the same for all simulated cases, i.e. 392 kWh/year. This could have been considered to be excluded from the analysis.

Note in Fig.21 that there is a significant higher energy consumption for the ECW controlled by solar radiation (Sun), TCW and PCW for Range 10-90 and Range 0-100 for all locations except for the PCW in Trondheim and Madrid. This is due to the fact that thresholds and control levels for the windows are set to high. A sensitivity analysis was conducted on Range 0-100, which shows that the total delivered energy was reduced significantly with lower thresholds and control levels. The ECW controlled by solar radiation (Sun) had the lowest total delivered energy when the threshold for the darkest state of the window was set at a global radiation level of 300 W/m^2 (Trondheim), 200 W/m^2 (Madrid) and 100 W/m^2 (Nairobi). The TCW had the lowest total delivered energy when the control levels for the clearest and darkest state of the tinting were set to 0-15°C (Trondheim), 0-15°C (Madrid) and 10-15°C (Nairobi). The PCW had the lowest total delivered energy when the control levels were set to 100-450 W/m^2 (Trondheim), 100-300 W/m^2 (Madrid) and 50-100 W/m^2 (Nairobi). It can also be seen that the total delivered energy increases from Range 10-90 to Range 0-100, which is due to a larger solar heat gain. The results from the sensitivity analysis will not be presented in more detail.

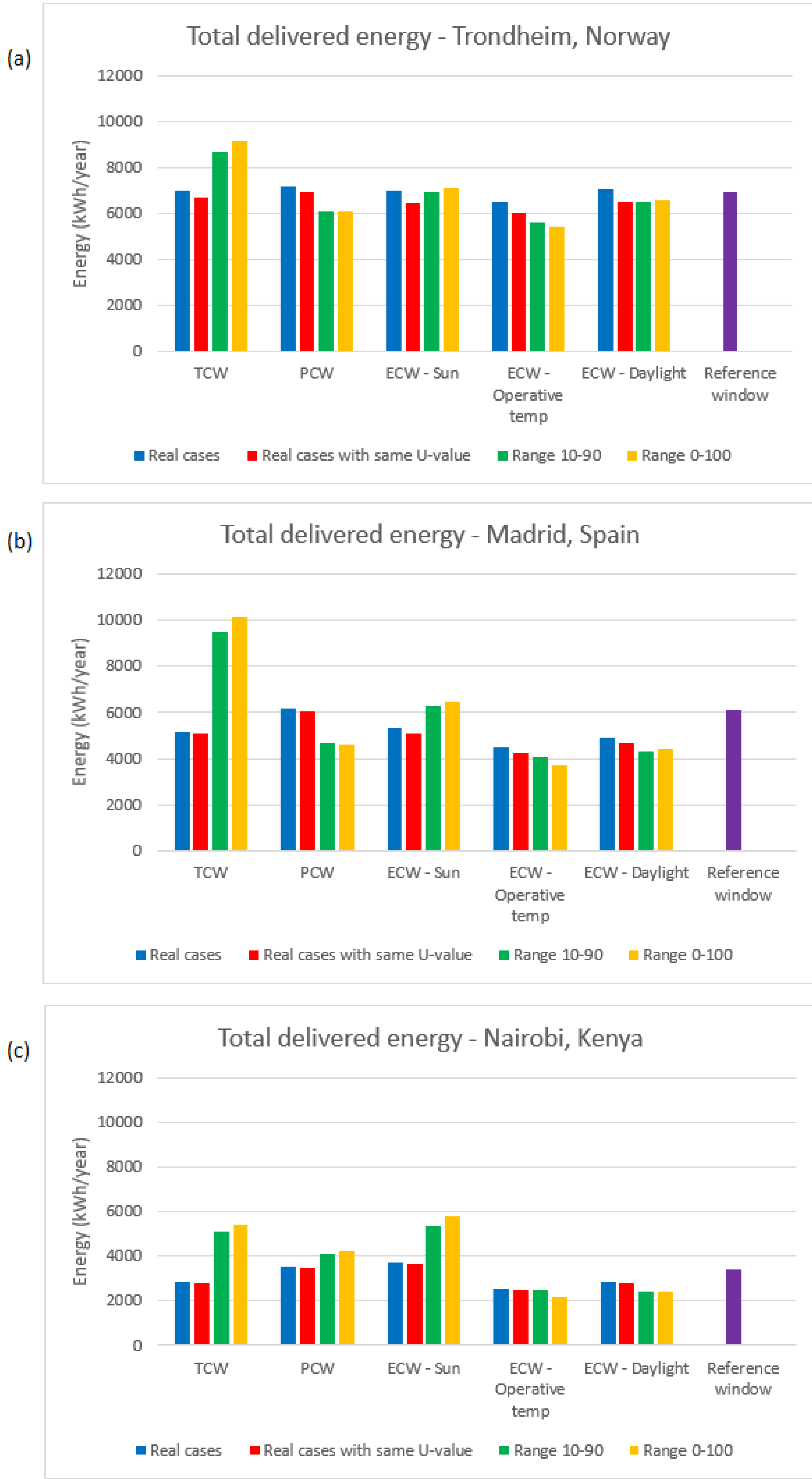


Fig.21. Total delivered energy for an entire year for all simulated cases, (a) Trondheim, Norway, (b) Madrid, Spain, and (c) Nairobi, Kenya.

When comparing the energy performance of the building with the reference window to the building with smart windows, it can be seen that most energy is saved due to a lower cooling demand for all cases and locations. Peak loads for cooling and solar gain are also significantly lower due to that the smart windows manage to block out the unwanted solar heat gain during cooling periods. This could potentially mean that cooling installations with less capacity could be installed in the building, and hence save cost.

Results for Trondheim

All results are in comparison to the reference window (100%), where good performance mean low energy consumption and bad performance mean high energy consumption. The ECW - Operative temperature shows the best performance with a total delivered energy of 94 % (real case), 87 % (real case with same U-value), 80 % (Range 10-90) and 78 % (Range 0-100). Highest energy consumption can be observed with TCW and PCW. TCW performs good for real cases but bad for Range 10-90 and Range 0-100 with a total delivered energy of 101 % (real case), 97 % (real case with same U-value), 125 % (Range 10-90) and 132 % (Range 0-100). PCW performs good for Range 10-90 and Range 0-100 but bad for real cases with a total delivered energy of 103 % (real case), 100 % (real case with same U-value), 88 % (Range 10-90) and 88 % (Range 0-100). ECW - Daylight shows no significant improvement with a total delivered energy of 102 % (real case), 94 % (real case with same U-value), 94 % (Range 10-90) and 95 % (Range 0-100). ECW - Sun shows no significant improvement with a total delivered energy of 100 % (real case), 93 % (real case with same U-value), 100 % (Range 10-90) and 102 % (Range 0-100). Table 8 shows the results for each simulated case divided into heating, cooling, equipment and lighting.

Table 8. Total delivered energy for all cases in Trondheim, Norway. Delivered energy for heating, cooling, equipment and lighting is shown for each case simulated.

		Case	Manufacturer	Product	Heating (kWh/year)	Cooling (kWh/year)	Equipment (kWh/year)	Lighting (kWh/year)	Total (kWh/year)
Real cases	Adaptive	TCW	Pleotint LLC	Solarblue	5917	633	392	31	6973
		PCW	Chameleon	Chameleon 53	5578	1156	392	27	7153
	Controllable	ECW - Sun	SAGE Electrochromics	Cool View Blue	5856	651	392	54	6953
		ECW - Operative temperature	SAGE Electrochromics	Cool View Blue	5815	253	392	65	6524
		ECW - Daylight	SAGE Electrochromics	Cool View Blue	6284	359	392	30	7065
Real cases with same U-value	Adaptive	TCW	Pleotint LLC	Solarblue	5618	660	392	31	6700
		PCW	Chameleon	Chameleon 53	5299	1184	392	27	6901
	Controllable	ECW - Sun	SAGE Electrochromics	Cool View Blue	5312	709	392	54	6466
		ECW - Operative temperature	SAGE Electrochromics	Cool View Blue	5291	273	392	67	6022
		ECW - Daylight	SAGE Electrochromics	Cool View Blue	5714	391	392	30	6527
Range 10-90	Adaptive	TCW	N/A[1]	N/A[1]	4643	3631	392	22	8687
		PCW	N/A[1]	N/A[1]	5049	629	392	22	6091
	Controllable	ECW - Sun	N/A[1]	N/A[1]	4775	1737	392	22	6926
		ECW - Operative temperature	N/A[1]	N/A[1]	4887	261	392	26	5566
		ECW - Daylight	N/A[1]	N/A[1]	5887	217	392	22	6518
Range 0-100	Adaptive	TCW	N/A[1]	N/A[1]	4559	4165	392	22	9138
		PCW	N/A[1]	N/A[1]	5125	530	392	49	6095
	Controllable	ECW - Sun	N/A[1]	N/A[1]	4763	1890	392	45	7089
		ECW - Operative temperature	N/A[1]	N/A[1]	4836	109	392	54	5391
		ECW - Daylight	N/A[1]	N/A[1]	5952	208	392	22	6572
		Reference window	Saint-Gobain	Cool-Lite 174+ar	5290	1217	392	24	6922

[1] Non-applicaple. Range 10-90 and Range 0-100 cases does not apply to any real product.

Results for Madrid

All results are in comparison to the reference window (100 %), where good performance mean low energy consumption and bad performance mean high energy consumption. Results for Madrid also shows that ECW - Operative temperature has the best performance with a total delivered energy of 72 % (real case), 69 % (real case with same U-value), 67 % (Range 10-90) and 60 % (Range 0-100). Worst performance can be observed with TCW and PCW. TCW performs good for real cases but bad for Range 10-90 and Range 0-100 with a total delivered energy of 85 % (real case), 83 % (real case with same U-value), 155 % (Range 10-90) and 166 % (Range 0-100). PCW performs good for Range 10-90 and Range 0-100 but bad for real cases with a total delivered energy of 101 % (real case), 99 % (real case with same U-value), 76 % (Range 10-90) and 75 % (Range 0-100). ECW - Daylight performs good for all cases with a total delivered energy of 80 % (real case), 76 % (real case with same U-value), 71 % (Range 10-90) and 72 % (Range 0-100). ECW - Sun performs good for real cases but bad for Range 10-90 and Range 0-100 with a total delivered energy of 87 % (real case), 83 % (real case with same U-value), 103 % (Range 10-90) and 106 % (Range 0-100). Table 9 shows the results for each simulated case divided into heating, cooling, equipment and lighting.

Table 9. Total delivered energy for all cases in Madrid, Spain. Delivered energy for heating, cooling, equipment and lighting is shown for each case simulated.

		Case	Manufacturer	Product	Heating (kWh/year)	Cooling (kWh/year)	Equipment (kWh/year)	Lighting (kWh/year)	Total (kWh/year)
Real cases	Adaptive	TCW	Pleotint LLC	Solarblue	2606	2158	392	22	5177
		PCW	Chameleon	Chameleon 53	2472	3311	392	19	6194
	Controllable	ECW - Sun	SAGE Electrochromics	Cool View Blue	2642	2209	392	61	5303
		ECW - Operative temperature	SAGE Electrochromics	Cool View Blue	2706	1304	320	89	4419
		ECW - Daylight	SAGE Electrochromics	Cool View Blue	2833	1658	392	22	4904
Real cases with same U-value	Adaptive	TCW	Pleotint LLC	Solarblue	2458	2188	392	22	5060
		PCW	Chameleon	Chameleon 53	2333	3334	392	19	6077
	Controllable	ECW - Sun	SAGE Electrochromics	Cool View Blue	2373	2245	392	61	5071
		ECW - Operative temperature	SAGE Electrochromics	Cool View Blue	2444	1322	392	90	4248
		ECW - Daylight	SAGE Electrochromics	Cool View Blue	2540	1686	392	22	4640
Range 10-90	Adaptive	TCW	N/A[1]	N/A[1]	2071	7014	392	15	9492
		PCW	N/A[1]	N/A[1]	2297	1956	392	15	4659
	Controllable	ECW - Sun	N/A[1]	N/A[1]	2168	3749	392	15	6323
		ECW - Operative temperature	N/A[1]	N/A[1]	2345	1318	392	22	4076
		ECW - Daylight	N/A[1]	N/A[1]	2661	1260	392	15	4327
Range 0-100	Adaptive	TCW	N/A[1]	N/A[1]	2041	7739	392	14	10186
		PCW	N/A[1]	N/A[1]	2469	1675	392	63	4599
	Controllable	ECW - Sun	N/A[1]	N/A[1]	2469	1675	392	63	4599
		ECW - Operative temperature	N/A[1]	N/A[1]	2365	858	392	76	3690
		ECW - Daylight	N/A[1]	N/A[1]	2773	1237	392	14	4415
		Reference window	Saint-Gobain	Cool-Lite 174+ar	2313	3401	392	17	6122

[1] Non-applicaple. Range 10-90 and Range 0-100 cases does not apply to any real product.

Results for Nairobi

All results are in comparison to the reference window (100 %), where good performance mean low energy consumption and bad performance mean high energy consumption. Results for Nairobi also shows that ECW - Operative temperature has the best performance for all cases except for Range 10-90 which has best performance with ECW - Daylight. ECW - Operative temperature has a total delivered energy of 75 % (real case), 72 % (real case with same U-value), 72 % (Range 10-90) and 64 % (Range 0-100). Worst performance has the ECW - Sun with a total delivered energy of 110 % (real case), 108 % (real case with same U-value), 157 % (Range 10-90) and 169 % (Range 0-100). ECW - Daylight performs good with a total delivered energy of 84 % (real case), 82 % (real case with same U-value), 71 % (Range 10-90) and 72 % (Range 0-100). TCW performs good for real cases but bad for Range 10-90 and Range 0-100 with a total delivered energy of 83 % (real case), 82 % (real case with same U-value), 148 % (Range 10-90) and 158 % (Range 0-100). PCW performs bad for all cases with a total delivered energy of 103 % (real case), 102 % (real case with same U-value), 121 % (Range 10-90) and 124 % (Range 0-100). Table 10 shows the results for each simulated case divided into heating, cooling, equipment and lighting

Table 10. Total delivered energy for all cases in Nairobi, Kenya. Delivered energy for heating, cooling, equipment and lighting is shown for each case simulated.

		Case	Manufacturer	Product	Heating (kWh/year)	Cooling (kWh/year)	Equipment (kWh/year)	Lighting (kWh/year)	Total (kWh/year)
Real cases	Adaptive	TCW	Pleotint LLC	Solarblue	813	1615	392	15	2834
		PCW	Chameleon	Chameleon 53	771	2347	392	12	3521
	Controllable	ECW - Sun	SAGE Electrochromics	Cool View Blue	809	2534	392	16	3751
		ECW - Operative temperature	SAGE Electrochromics	Cool View Blue	876	1201	392	96	2564
		ECW - Daylight	SAGE Electrochromics	Cool View Blue	837	1646	392	14	2889
Real cases with same U-value	Adaptive	TCW	Pleotint LLC	Solarblue	749	1639	392	15	2795
		PCW	Chameleon	Chameleon 53	711	2370	392	12	3483
	Controllable	ECW - Sun	SAGE Electrochromics	Cool View Blue	693	2585	392	16	3686
		ECW - Operative temperature	SAGE Electrochromics	Cool View Blue	758	1231	392	97	2477
		ECW - Daylight	SAGE Electrochromics	Cool View Blue	722	1690	392	14	2817
Range 10-90	Adaptive	TCW	N/A[1]	N/A[1]	634	4043	392	8	5076
		PCW	N/A[1]	N/A[1]	639	3084	392	8	4123
	Controllable	ECW - Sun	N/A[1]	N/A[1]	624	4362	392	8	5385
		ECW - Operative temperature	N/A[1]	N/A[1]	729	1290	392	50	2460
		ECW - Daylight	N/A[1]	N/A[1]	717	1314	392	8	2430
Range 0-100	Adaptive	TCW	N/A[1]	N/A[1]	625	4374	392	8	5399
		PCW	N/A[1]	N/A[1]	625	4374	392	8	5399
	Controllable	ECW - Sun	N/A[1]	N/A[1]	612	4780	392	9	5793
		ECW - Operative temperature	N/A[1]	N/A[1]	749	950	392	98	2188
		ECW - Daylight	N/A[1]	N/A[1]	711	1339	392	7	2449
		Reference window	Saint-Gobain	Cool-Lite 174+ar	708	2311	392	9	3419

[1] Non-applicaple. Range 10-90 and Range 0-100 cases does not apply to any real product.

4.2 ECW controlled by operative temperature in Madrid, Spain

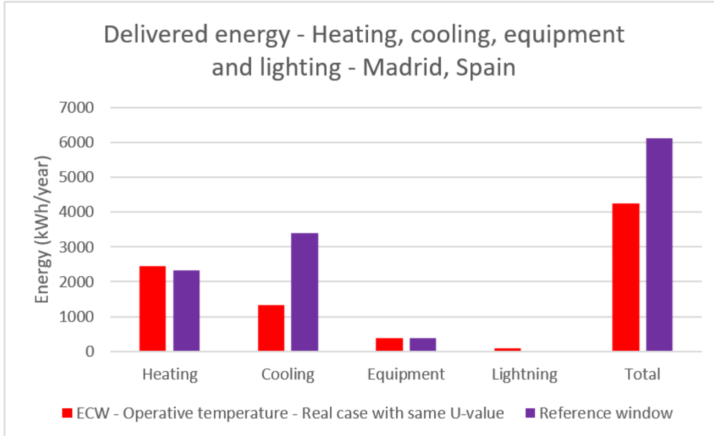
The results for ECW controlled by operative temperature will further be presented in more detail due to that it has been shown to be the best performing approach, with the lowest energy consumption for almost all cases and locations. The following results presented are a comparison between the ECW real case with same U-value controlled by operative temperature and the reference window in Madrid, Spain.

4.2.1 Delivered energy and peak loads

The total delivered energy for the reference window is divided in into 55 % cooling, 37 % heating, 6 % equipment and 3 % lighting. From Fig.22 (a) it can be seen that the largest energy savings are due to a lower cooling demand for the building with the ECW. Compared to the reference window (100 %), the cooling demand is decreased to 39 %. The heating demand is slightly increased to 106 %. Lighting is increased to a lot to 547 % while equipment is the same at 100 %. Note that equipment and lighting are small energy posts compared to heating and cooling. In Table 11 (a) the delivered energy is listed for each energy post.

The peak loads show the maximum power (W/m^2) that occurs during the entire simulation period. Collected for both cases are the solar heat gain peak load, heating peak load and cooling peak load. From Fig.22 (b) it can be seen that the cooling peak load and the solar heat gain peak load are significantly lower compared to the reference window with 47 % and 69 %, respectively. The heating peak load is slightly higher for the ECW window with 103 %. Table 11 (b) shows the peak loads for solar heat gain, heating and cooling for both cases.

(a)



(b)

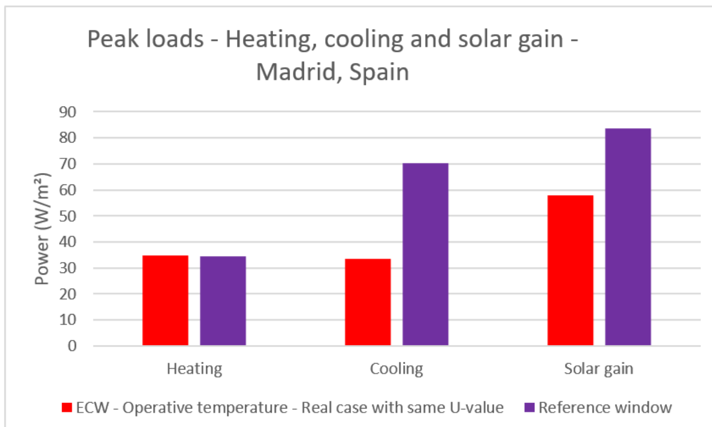


Fig.22. Delivered energy and peak loads for the ECW and the reference window. (a) Delivered energy divided into heating, cooling, equipment and lighting. (b) Peak loads for heating, cooling and solar gain.

Table 11. Delivered energy and peak loads for the ECW and the reference window. (a) shows the delivered energy divided into heating, cooling, equipment and lighting. (b) shows the peak loads for heating, cooling and solar gain.

(a) Delivered energy (kWh/year)

Window technology	Heating	Cooling	Equipment	Lightning	Total
ECW - Operative temperature - Real case with same U-value	2444	1322	392	90	4248
Reference window	2313	3401	392	17	6122

(b) Peak loads (W/m²)

Window technology	Heating	Cooling	Solar gain
ECW - Operative temperature - Real case with same U-value	35	33	58
Reference window	34	70	84

4.2.2 Energy balance

The energy balance shows the sensible (not including latent heat) heat balance for the entire zone (EQUA Simulation AB, 2018h). Data is presented for each month as well as for the entire simulation period. In addition, each heat flux is divided into "during heating", "during cooling" and "rest of time". Positive values mean that heat is flowing in to the building (heat gain) and negative values mean that heat flowing out of the building (heat loss). A gain is preferred when it occurs during a heating demand and unwanted during a cooling demand. See Table 12 for an explanation of each category in the energy balance. Same principles apply to the time dependent energy balance. These are however not collected during heating or cooling hours.

Table 12. Energy balance explanations. The explanations is valid for both monthly and time dependent energy balances.

Category	Explanation
Envelope transmission	Heat gained via conduction through external walls, floor and roof.
Window and solar	Heat gain through external windows, i.e. through long- and short-wave radiation (direct, diffuse and indirect via absorbed and reemitted solar radiation) as well as via conduction through window pane and frame.
Occupants	Heat from people in the zone, excluding heat from perspiration.
Equipment	Heat from equipment in the zone, e.g. computer etc.
Lighting	Heat from artificial lighting.
Heating	Heat from ideal heaters
Cooling	Heat from ideal coolers
Window[1]	Heat gain via conduction through window pane and frame
Solar[1]	Heat gain via long and short wave radiation (direct, diffuse and indirect via convection and radiation)

[1]Window and Solar are not represented as separate posts in the monthly and time dependent energy balances.

Figure 23 shows the monthly energy balance for (a) the ECW and (b) the reference window. It can be seen that there is a significant difference in the energy balance between the building with the ECW and the reference window. From the energy balance of the reference window it can be seen that the building has a high heating demand during the winter periods and a high cooling demand during the summer periods. The building envelope transmission is also higher during the winter periods, while the solar heat gain is quite even during the entire year. From the energy balance of the ECW is can be seen that the cooling demand and the solar heat gain is significantly decreased across the entire year, while the heating demand and building envelope transmission is quite similar as for the reference window with higher values during the winter period.

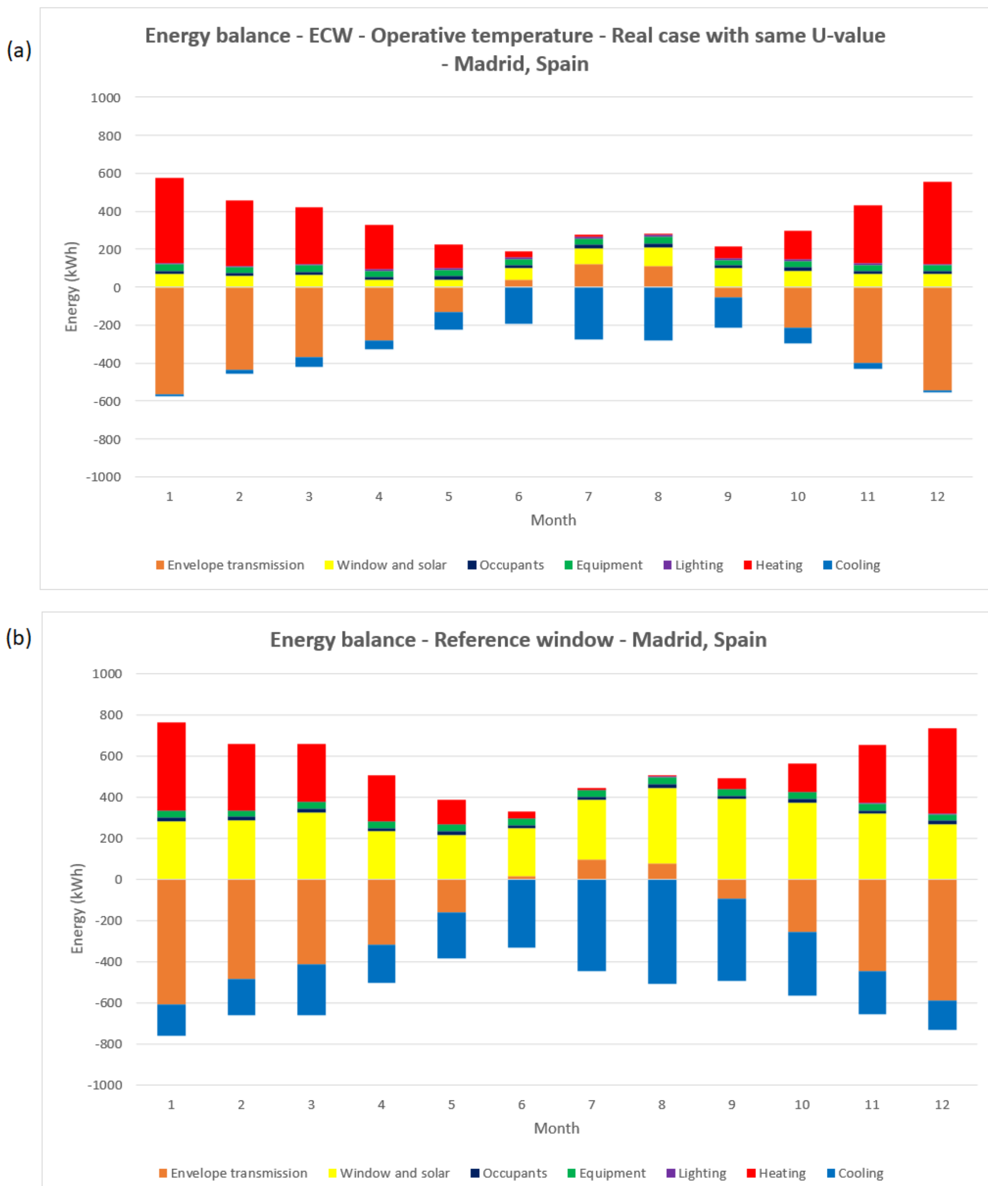


Fig.23. Energy balance for Madrid, Spain. (a) Energy balance for ECW - Operative temperature - Real case with same U-value, and (b) Energy balance for reference window.

Figure 24 shows the time dependent energy balance during a summer day for (a) the ECW and (b) the reference window. These values take into consideration the building envelope areas of each building component and values are given in Watts (W). It can be seen that during the middle of the day, there is a high cooling demand for the reference window due to lots of solar heat gain. The cooling demand is decreased significantly when the solar heat gain is rejected by the tinting of the ECW.

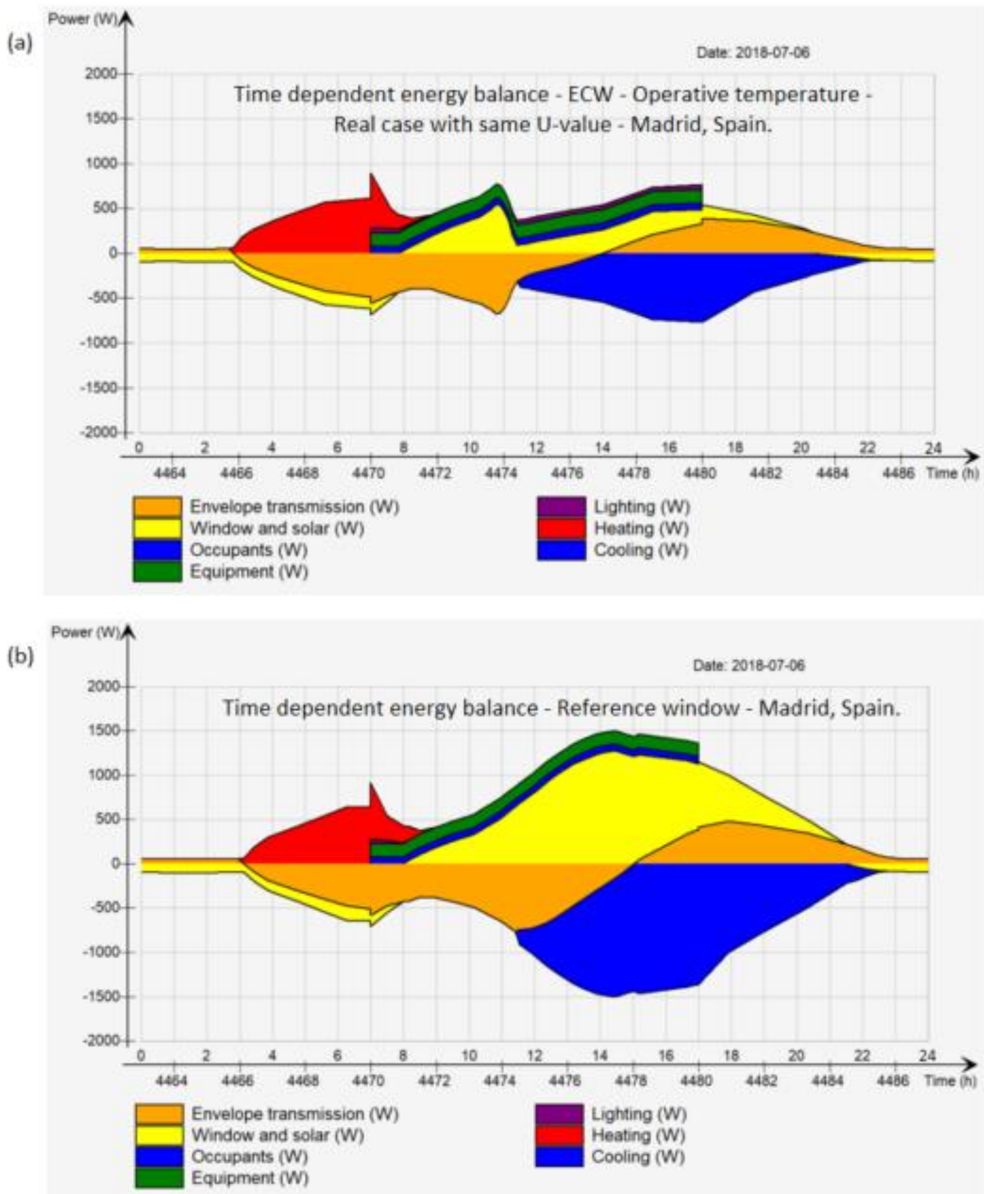


Fig.24. Energy balance as a function of time during a summer day in Madrid, Spain. (a) ECW - Operative temperature - Real case with same U-value, and (b) Reference window.

4.2.3 Total solar heat gain

The difference of the heat gain due to only solar radiation (Solar) between the building with the ECW and the reference window can be obtained by deducting the heat gain via conduction through the window pane and frame (Window) from the heat gain through windows (Window and solar). The following equation is used:

$$Solar = Window\ and\ solar - Window \qquad (4)$$

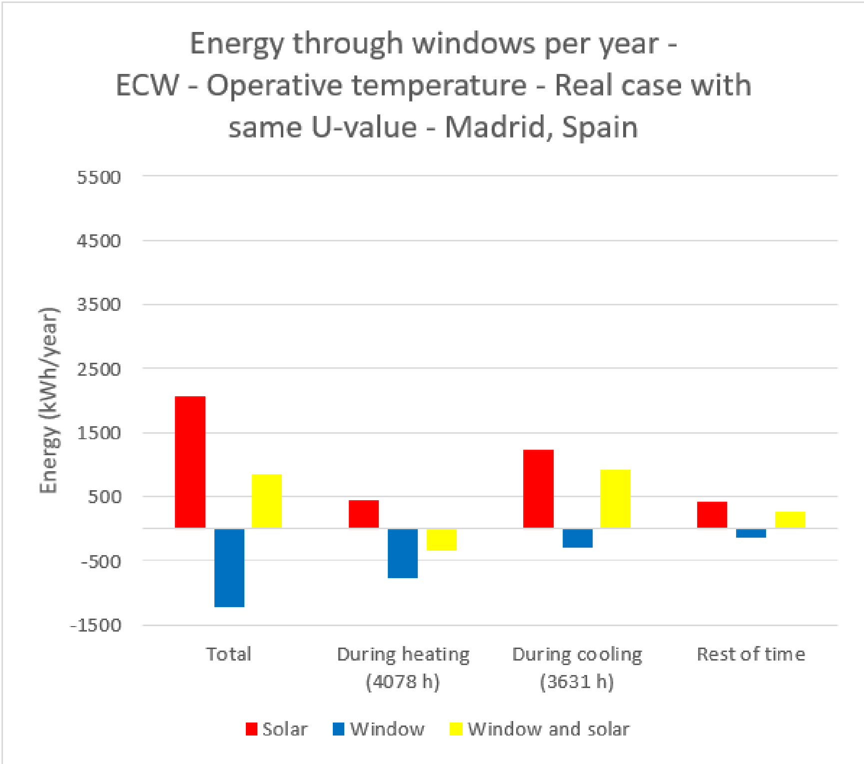
where

- "Solar" contains the heat gain via direct and diffuse solar radiation as well as the indirect heat gain via absorbed and reemitted solar radiation.
- "Window and solar" contains the heat gain via direct and diffuse solar radiation as well as the indirect heat gain via absorbed and reemitted solar radiation and conduction through window pane and frame.
- "Window" contains the heat gain via conduction through window pane and frame.

The "Window and solar" values are determined by the g-value in IDA ICE.

See Fig.25 for the yearly results for both (a) the ECW and (b) the reference window. See Figure 26 for the monthly results. The yearly results are divided into "during heating", "during cooling" and "rest of time". It can be seen both for the yearly and monthly values that the heat gain via conduction through window pane and frame (Window) is equal for both cases while the ECW manage to reject large parts of the solar heat gain (Solar). Note also that the solar heat gain is mainly rejected during cooling periods.

(a)



(b)

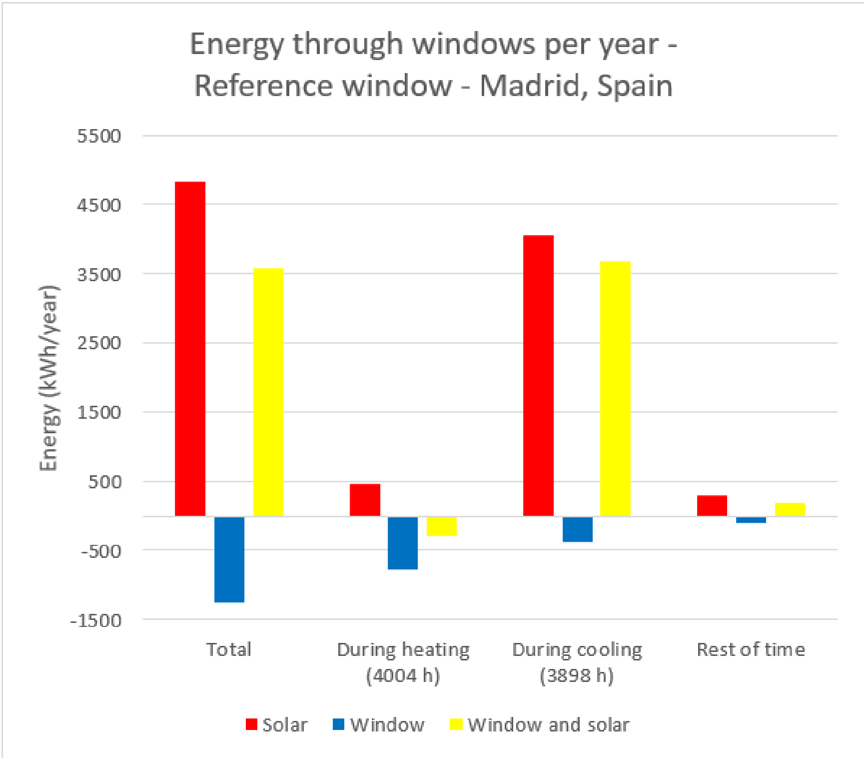
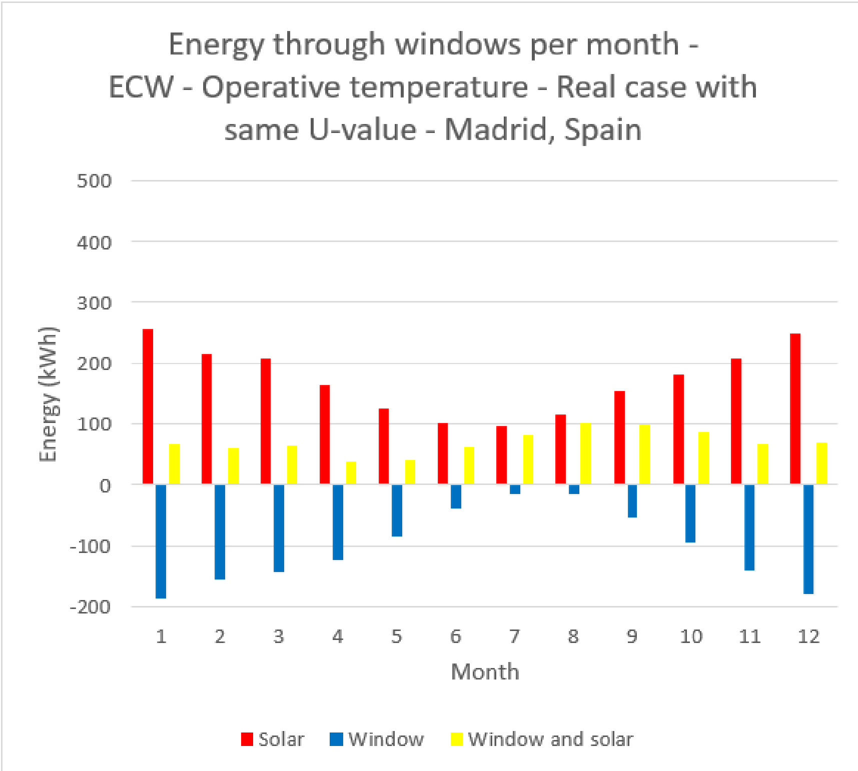


Fig.25. Energy through windows per year divided into Solar, Window and Window and solar. (a) ECW - Operative temperature - Real case with same U-value, and (b) Reference window.

(a)



(b)

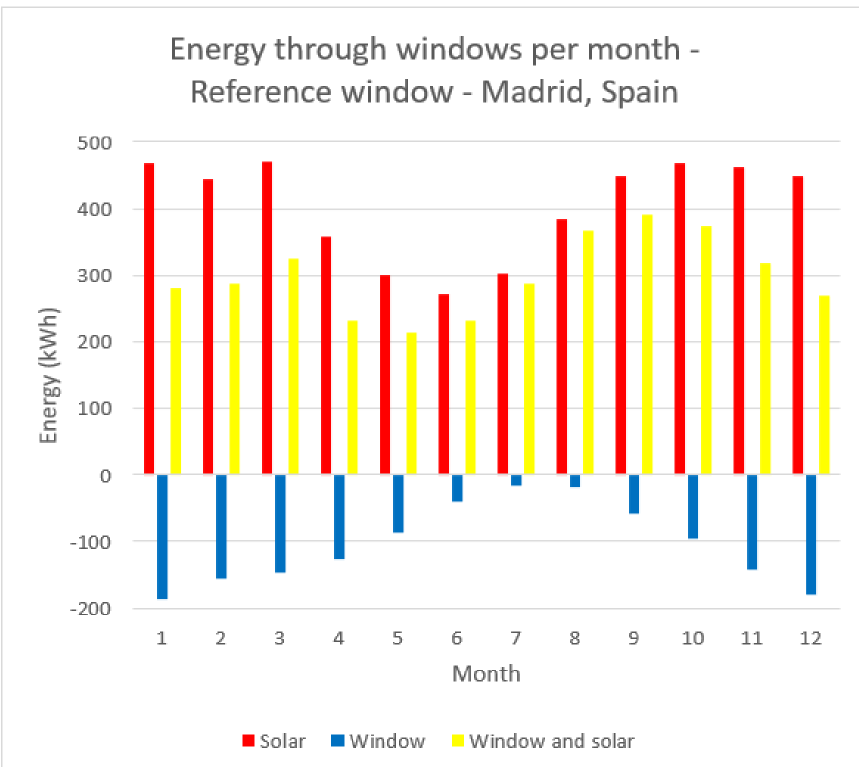


Fig.26. Energy through windows per month divided into Solar, Window and Window and solar. (a) ECW - Operative temperature - Real case with same U-value, and (b) Reference window.

Figure 27 shows the time dependent total solar heat gain that is entering through each window for both (a) the ECW and (b) the reference window. Here the indirect solar heat gain is included. Note here that the diagram only shows values for one window.

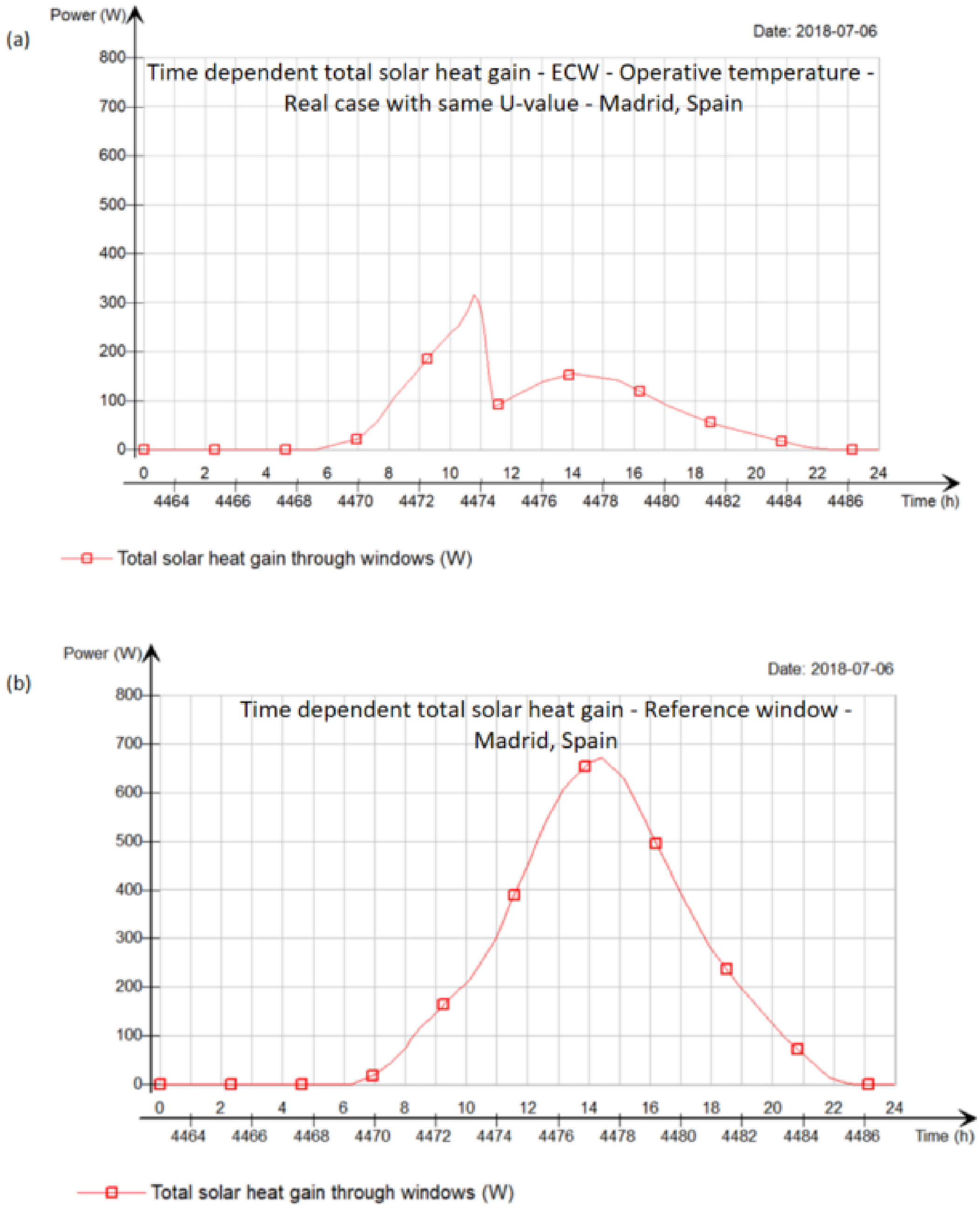


Fig.27. Total solar heat gain through each window as a function of time. (a) ECW - Operative temperature - Real case with same U-value, and (b) Reference window.

4.2.4 Direct and diffuse solar heat gain

To see the solar heat gain due to only direct and diffuse solar radiation, similar is done for the time dependent values as for the energy balance. The difference of the heat gain due to direct and diffuse solar radiation (Solar radiation) between the building with the ECW and the reference window is obtained by deducting the heat gain via infrared radiation and heat conduction (infrared rad. and heat conduction) from the heat gain through windows (Window and solar). Note here the indirect solar heat gain through absorption is not accounted for. The following equation is used:

$$Solar\ radiation\ = Window\ and\ solar - infrared\ rad.and\ heat\ conduction \qquad (5)$$

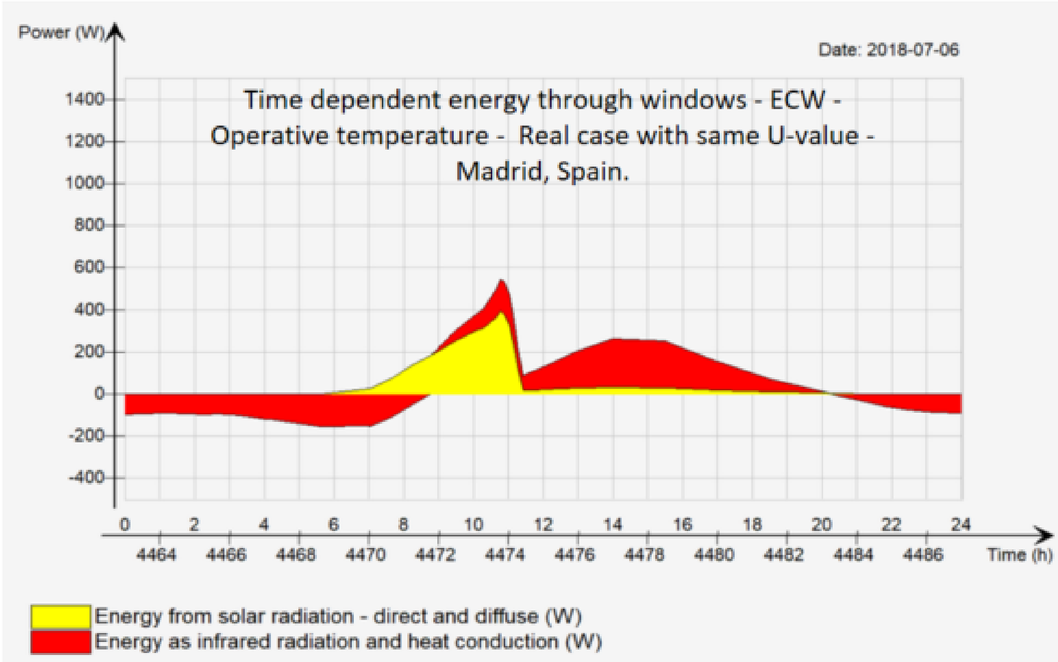
where

- "Solar radiation" contains the heat gain via direct and diffuse solar radiation.
- "Window and solar" contains the heat gain via direct and diffuse solar radiation as well as the indirect heat gain via absorbed and reemitted solar radiation and conduction through window pane and frame.
- "Infrared rad. and heat conduction" contains the heat gain via absorbed and reemitted solar radiation and conduction through window pane and frame.

In IDA ICE the "Window and solar" is determined by the g-value, the "Solar radiation" is determined by T_{sol} and the "Infrared rad. and heat conduction" is determined by both the g-value and T_{sol}.

Figure 28 shows the time dependent values for the direct and diffuse solar radiation and the infrared and conduction through window pane and frame. It can be seen that the ECW rejects lots of the direct and diffuse solar heat gain compared to the reference window. However, the heat gain via infrared radiation and heat conduction is slightly higher for the ECW.

(a)



(b)

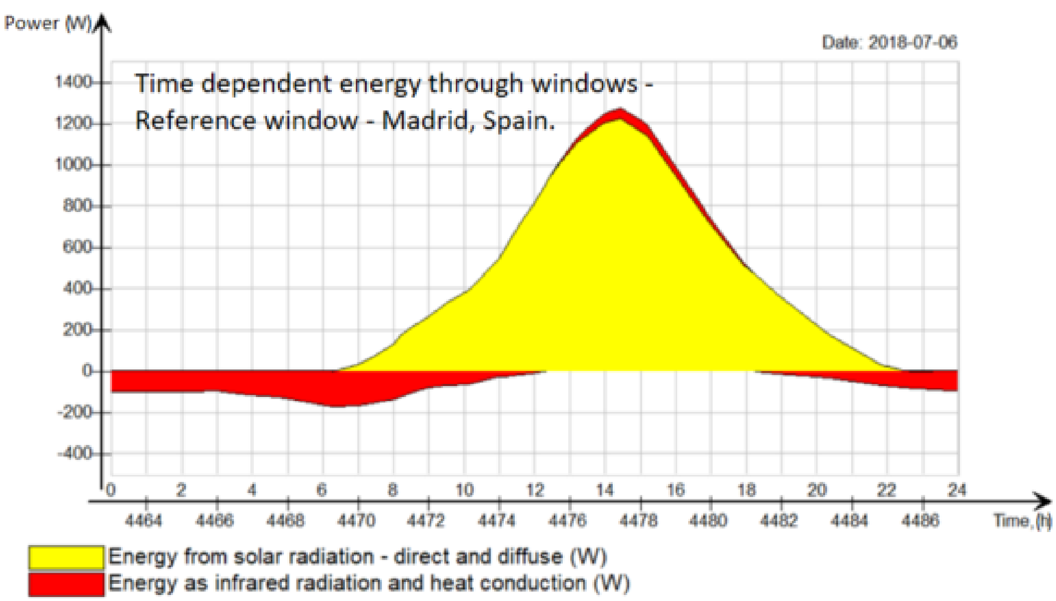


Fig.28. Energy from solar radiation, infrared radiation and heat conduction as a function of time.(a) ECW - Operative temperature - real case with same U-value, and (b) Reference window.

5 Discussion

It was indicated in previous studies that smart windows should have greater impact on the energy performance of buildings in warmer and sunnier climates ((Dussault and Gosselin, 2017), (Piccolo et al., 2018), (Reynisson, 2015)), which also proves to be correct in this study. However, the energy saving potential for ECW are lower than what have been found in previous studies by Reynisson (2015) and might be due to the fact that the WWR is lower and a different control strategy was used for the ECW. The building model of Reynisson (2015) also only consist of one external wall, which is the one containing windows. The other walls are modelled as internal walls with adiabatic conditions (no heat transfer). This could have been considered to be a more suitable way to model the building to get a larger impact on the energy consumption by implementing smart windows.

From this study it can be seen that the ECW controlled by operative temperature has the lowest total energy consumption of all smart windows for all cases and locations. By observing the real case with same U-value, the lowest energy demand can be seen in Madrid with a total delivered energy of 69 % compared to the reference window. In Trondheim and Nairobi the corresponding total delivered energy is 87 % and 72%, respectively. The cooling demand was however lowest in Trondheim with 22 %, while in Madrid it was 39 % and in Nairobi it was 53 % compared to the reference window. But since the cooling is a smaller part of the total energy consumption for Trondheim, it has a less impact on the total delivered energy compared to Madrid and Nairobi. The heating demand does not change with 100 % for Trondheim but increases to 106 % for Madrid and 107 % for Nairobi. The lighting demand however is very high with 278 % in Trondheim, 547 % in Madrid and 1051 % in Nairobi. But since this is a small part of the total energy demand, it has little effect in this work, but should be taken into consideration for cases where lighting is a larger part of a building's energy consumption. It could have been argued that the lighting would have a larger input in a real case scenario, hence it would also have a larger effect on the results.

Generally, it would be suggested that the smart windows would improve their performance as the window properties would improve, i.e. a lower U-value and an increased interval for when the windows are in their clearest and darkest state. By having a high value as possible for the clearest state, the window can allow for more solar heat when wanted and by having a low value as possible for the darkest state, the window can block out more solar heat when unwanted. Since most of the energy savings are due to a reduced cooling demand, it would also be expected better performance in warmer and sunnier climates. Cooling demand is due to both solar heat gain and temperature differences between indoor and outdoor environment. It would be reasonable to think that the part of the cooling demand due to solar heat gain would be larger in colder locations and that the part of cooling demand due to higher outdoor temperatures would be larger in warmer locations. However, it can be seen that there is some deviation from this expected trend considering location, window technology (TCW, PCW or ECW) and optical properties (real cases, real cases with same U-value, Range 10-90 and Range 0-100). For the real cases, the results are quite as expected with a slight improvement with a lower U-value at all locations. The improvement is however largest in Madrid with a total delivered energy of 69 % for the ECW -Operative temperature compared to the reference window followed by 72 % in Nairobi and 87 % in Trondheim. The cooling demand for the same case follows a bit different trend, where the largest savings compared to reference window is in Trondheim with 22 % followed by 39 % in Madrid and 53 % in Nairobi. So, the savings for cooling are greater in percentage further north but since the cooling demand is a larger part of the total energy demand further south, it has a greater total savings at southern locations. When the location is “too far” south (Nairobi) the decreased savings in cooling demand are too low to perform any better on total delivered energy. This may be due to several factors such as the position of the sun (sun path), which is higher in Nairobi compared to Trondheim, the orientation of the windows (south in this case) and the climate in general, i.e. the amount of direct and diffuse solar radiation, dry-bulb temperature and cloudness. Note also that in this work the COP is set to 1, which most probably would not be the case in a real scenario and hence the ratio of heating and cooling energy consumption would be different.

For the Range 10-90 and Range 0-100 cases, the results shows various results with improved optical parameters. The ECW controlled by operative temperature and daylight follows the expected trend and performs better than the real cases. This is also the case for the PCW (in Trondheim and Madrid). The ECW controlled by solar radiation (Sun), the TCW and the PCW (in Nairobi) however shows worse performance than the real cases. Since all the optical parameters are the same for all cases, it highlights the importance of having the right control strategy with thresholds that suits the optical properties of the window, location and corresponding climate for the building. The fact that the ECW controlled by solar radiation (Sun) and daylight does not directly target the energy consumption of heating and cooling, but the solar radiation coming through the windows and the daylight at a workplane may have a negative effect on the heating and cooling, respectively.

The control levels that were set in this study is also clearly not the most optimal. A sensitivity analysis was conducted on the control levels of the control strategies for the ECW controlled by solar radiation (Sun), the TCW and the PCW for Range 0-100 in Trondheim, Madrid and Nairobi. This is not presented in this work in detail, but it shows that the thresholds and control levels set in this study are too high and that all technologies shows a lower total delivered energy demand and more according to the expected trend with lower thresholds and control levels. However, the optimal control levels for the TCW and the PCW are shown also to be so small that they are close to an on/off control strategy rather than a continuous tinting strategy. This study was however not meant to optimize control strategies of different technologies, merely to show the energy saving potential of different smart window technologies. The mismatch of control levels for the TCW and PCW makes the comparison a bit unfair but highlights yet again the importance of customized control strategies and thresholds and the importance of these being provided by manufacturers. Still, taken the sensitivity analysis into consideration, the best performing technology proves to be the ECW controlled by operative temperature.

The optical properties of the reference window are different from the clearest state of the smart windows. Since the results show that the energy savings are mainly due to a reduced cooling demand, it would be reasonable to think that the difference between the cooling demand for the smart windows and the reference window would be greater with a higher g-value and T_{sol} for the reference window, and vice versa for a lower g-value and T_{sol}. When comparing the real cases of the smart windows the optical properties are quite different. By observing the g-value, the following can be seen:

- The TCW has a lower g-value in its clearest state and higher g-value in its darkest state (0.27-0.14) compared to the ECW.
- The PCW has a very narrow interval between the clearest and darkest state (0.40-0.36) with values higher for both states compared to the TCW.
- The ECW has the highest g-value in its clearest state and the lowest in its darkest state (0.46-0.09).

The ECW will hence be able to let in the most solar heat when wanted and to block out when unwanted. The TCW will let in less when wanted and block out less when unwanted compared to the ECW. The PCW has the narrowest interval at relative high levels which makes it similar to the reference window. The same goes for T_{sol} where the following can be seen:

- Both TCW and PCW have quite low values for both the clearest state and the darkest state (0.16-0.05)
- The ECW has the largest interval with the highest value at the clearest state and lowest at the darkest state (0.30-0.01).

Note that due to missing information from the manufacturer of the PCW, the same values are used as for TCW. The results might have been different if real values from the manufacturer were provided, including the U-value of the PCW. T_{vis} values are relatively equal for the ECW (0.40-0.023) and TCW (0.38-0.08) in their clearest state while PCW are quite high with a narrow interval (0.52-0.42).

All mentioned above have an impact on the results since a higher value for the clearest state can allow for more solar radiation while a lower value for the darkest state can reject more solar radiation. The bad performance for the PCW might be explained by this in addition to the mismatch of control levels. It can be seen that the performance is close to the reference window at all locations which could be explained by that the g-values are close to the same with a small difference between the clearest and darkest state. TCW has somewhat poor g-values which would not benefit the performance of the technology. However, it is difficult to determine the impact of the various optical parameters for TCW and PCW due to the mismatch in thresholds for the control levels. The superior performance of the ECW - Operative temperature would also be having an advantage of that it has the largest span in the g-value.

The difference in T_{vis} values would affect the daylight in the zone and hence the artificial lighting. This has however a small impact in this study since the artificial lighting is a small part of the total delivered energy. Note that T_{vis} is higher for the reference window, which mean that the daylight is better utilized compared to the smart windows in their clearest state and which also contribute to the lower energy demand for artificial lighting for all real cases. ECW controlled by daylight has the best performance in lighting demand of the ECW control strategies due to that it tries to maintain 500 lux. Note here however due to the fact that IDA ICE does not take into consideration the independency of wavelength, the daylight values are deviating from “true” values. A fairer comparison of the respective technologies could have been seen for the Range 10-90 and Range 0-100 when the optical values are the same. Unfortunately, the mismatch of control levels does not allow for this.

The spectral dependency would have been possible to model in the “detailed window” model in IDA ICE. Here, the software makes a layer by layer computation of multiple reflections and each layer temperature is computed. The optical calculations in the solar range is made for each wavelength and the values are then integrated to average values according to EN 410 (EQUA Simulation AB, 2018f). However, due to missing information from producers this was not possible. If more information about the windows were provided, more accurate results may have been obtained by using the detailed window model. However, Equa is working on a model for smart windows and most probably this will make the modelling and results of simulating smart windows more seamless and accurate.

6 Further work

There are several possible research opportunities highlighted by this work. To check how accurate the simulations that are conducted in this work, it would be interesting to conduct the same simulations in another building performance simulations software to see if the results would be similar using the same building model from BESTTEST case 600. This would also contribute to the validation of how well IDA ICE handles the modelling of smart windows. As mentioned, Equa (the company behind IDA ICE) is currently working on a beta-version for handling smart windows, which would be interesting to use for the same simulations. It was found in this study that the performance of smart windows is dependent on the correct control strategies and control levels for each window to match the location and optical parameters, hence a parameter optimization study would be of interest. For the electrochromic window it would of interest to include a control strategy based on visual comfort, i.e. glare. It would also be of interest to see how the results would turn out with a larger part of artificial lighting, WWR and adiabatic conditions for the external walls. How the smart windows would affect the thermal comfort would also be of interest. In addition to the theoretical cases investigated, a similar case with a constant high T_{vis} would have been interesting to simulate. In this case the smart window would be able to allow for daylight while rejecting the solar heat gain when unwanted.

7 Conclusions

For this work, information has been collected from manufacturers about commercially available adaptable and controllable smart window products, i.e. thermochromic windows, photochromic windows and electrochromic windows, and is presented as a comprehensive state-of-the-art review. Furthermore, selected windows have been used for energy simulations. The electrochromic windows have been simulated using three different control strategies based on operative temperature, daylight and solar radiation. One product has been chosen from each technology to be simulated in the software package IDA ICE at three separate locations (Trondheim, Madrid and Nairobi) and has been compared to a normal static window without shading, denoted the reference window. The same products have also been simulated using the same U-value as for the reference window. In addition, two theoretical cases (Range 10-90 and Range 0-100) have been simulated, where the optical properties take on fictious values between 10 to 90 % and 0 to 100 % transmittance, respectively.

The results shows that the building with electrochromic window controlled by operative temperature has the lowest energy consumption of all technologies with a total delivered energy of 94-60 % compared to the reference window depending on case and location. Most energy savings are due to a lower cooling demand while the impact on heating demand is relatively low. The performance of smart windows is also very dependent on the control strategies, optical properties and what thresholds are set for the control levels. The results are varying between cases due to the inputs of these parameters and some comparisons can be considered not representative of the technology due to this fact. To properly be able to conduct an energy performance simulation comparison between technologies and products, information parameters such as U-value, g-value, T_{sol}, T_{vis}, control levels and threshold levels for products are of absolute necessity and should hence also be provided by manufacturers.

Acknowledgements

Valuable support and feedback on the work done in the software package IDA ICE has been provided by Bengt Hellström at Equa Simulation AB, especially concerning the creation of the control strategies and how to model smart windows in IDA ICE. The work has been supported by

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Appendix

A.1 Solar path – Trondheim, Madrid and Nairobi

Since this study is focusing on the energy performance of buildings using smart windows in different locations, the suns position in the sky will be an important variable when analyzing the results. Figure 29, Fig.30 and Fig.31 shows the annual solar path for Trondheim, Madrid and Nairobi, respectively. The green line is representing the suns path on June 21^{st} (June solstice) and the blue line is representing the suns path on December 21^{s} (December solstice) The circles represent the elevation angle and by moving around the circle the azimuth angle can be read. The outermost circle represents 0° elevation and the center represents 90° elevation. North represents 0° azimuth angle and south represents 180° azimuth angle. The yellow area represent the solar path during an entire year. It can be seen that the solar elevation is higher for locations further south, i.e. 68° in Nairobi, 73° in Madrid and 50° in Trondheim during summer, and 68° in Nairobi, 38° in Madrid and 4° in Trondheim during winter. Note that the solar elevation in Nairobi is highest during Autumn and Spring. Also, the increased difference in how long the sun is present in the sky for locations further north. For example, in Trondheim the sun is up on the sky a very short time in winter compared to summer, while in Nairobi the sun is up in the sky more evenly throughout the year.

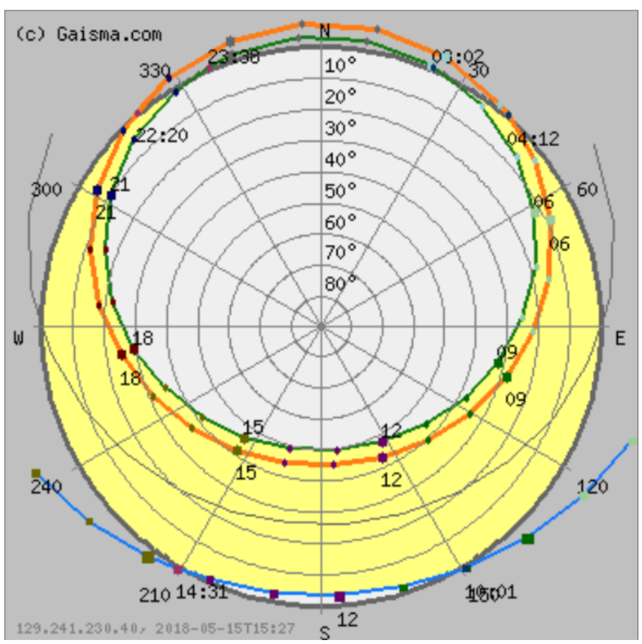

Fig.29. Solar path for Trondheim, Norway. The yellow area shows where the sun will move throughout an entire year (Gaisma, 2018c).

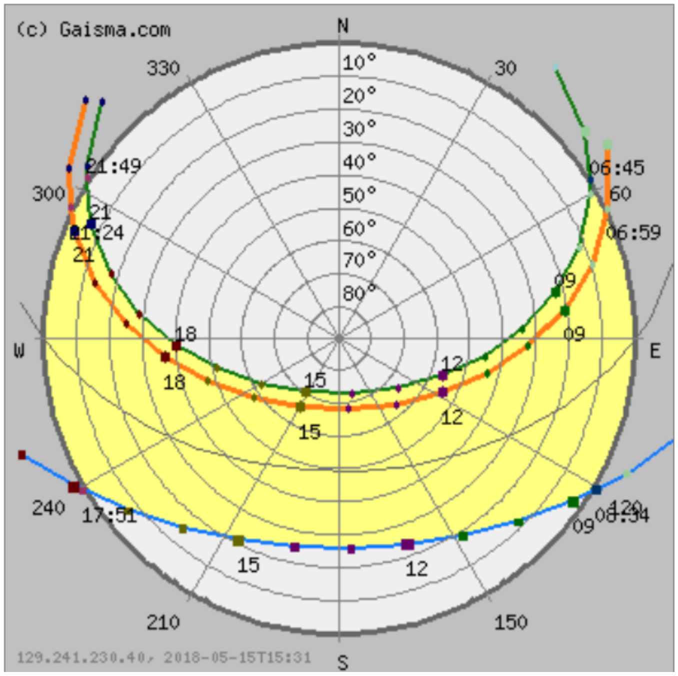

Fig.30. Solar path for Madrid, Spain. The yellow area shows where the sun will move throughout an entire year (Gaisma, 2018a).

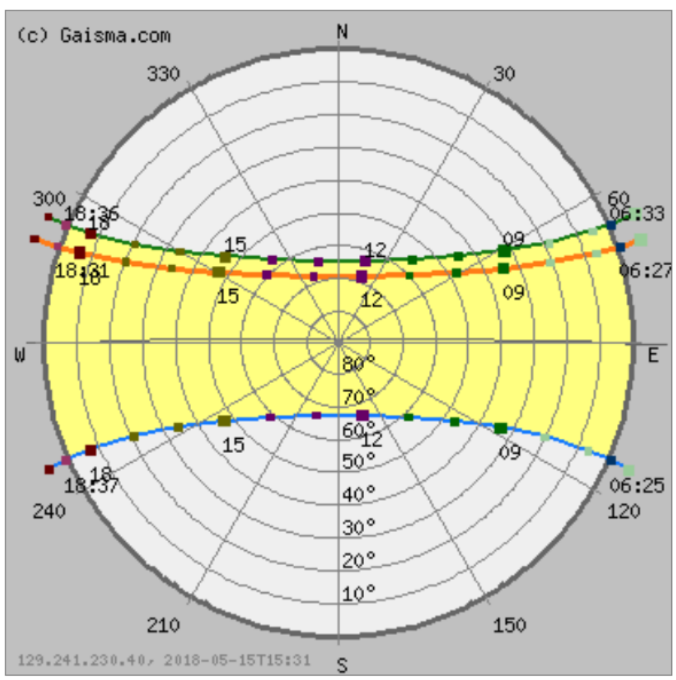

Fig.31. Solar path for Nairobi, Kenya. The yellow area shows where the sun will move throughout an entire year (Gaisma, 2018b).

A.2 Input information in IDA ICE

In addition to the building geometry, climate and location settings, the model consists of various user defined settings for the various systems of the building. Among those are the internal gains (lighting, occupants and equipment) and associated setpoints. See Table 13 for an overview of the specific user inputs of the most importance for this work. These settings are the same for all simulated cases, where only the windows and associated control strategies will vary. It should also be noted that there are several other input options in IDA ICE. However, these parameters are of no interest to investigate in this study, therefore these have been left untouched and set to default. Since this is a comparison study, these settings will affect the results in an equivalent way and does not change the objective outcome negatively. The modelling of the heating and cooling of the building is done in IDA ICE by so called ideal heaters and coolers. These have no physical representation in the model and are set to 10 000 W each such that they always will be able to meet the heating and cooling demands to obtain the setpoints for the zone. No air handling unit is connected to the building and heating for domestic hot water is not considered in the model. All energy delivered to the building are electric and no distribution losses are accounted for. Also, there are no heat losses due to thermal bridges, infiltration or other system losses. These factors are of no interest in this study and makes the comparison of the simulated cases easier.

Table 13. User defined inputs in IDA ICE.

Category	**User defined settings**		
Control setpoints	**Min**	**Max**	**Comments**
Temperature (°C)	21	25	Setpoints for heating and cooler controller. Ideal heaters and coolers with maximum power of 10 000 W. A PI-controller is used to keep the room air temperature at setpoints.
Daylight at workplace (Lux)	100	500	Light intensity at the workplane at which maximum artificial light is turned on and off.
Internal gains	All internal gains are set to be operative during occupant hours 07-17 on weekdays.		
Artificial lighting	1 unit of 50 W rated input per unit and 12 lm/W. The lighting is positioned in the middle of the zone, see Figure 32.		
Occupants	1 person with activity level equal to 1 MET (reading, seated) with a constant clothing of 0.85 ± 0.25. Activity layer and clothing are both according to the Fanger model and the software automatically adapts between limits to obtain comfort. The person is positioned in the middle of the zone with a height of 0.6 m, see Figure 33.		
Equipment	1 unit that emitts 150 W.		
Windows	Window properties will vary between each simulated case and more detailed information can be found in Table 7.		
Frame	Fraction of the total window area is 10 % with an U-value of 2 W/(m²K). The window is never open.		

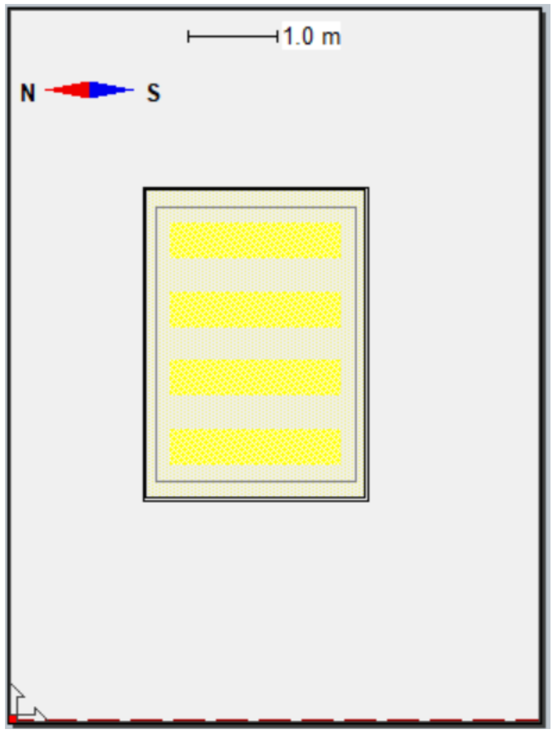

Fig.32. Position of artificial lighting at the ceiling in the zone.

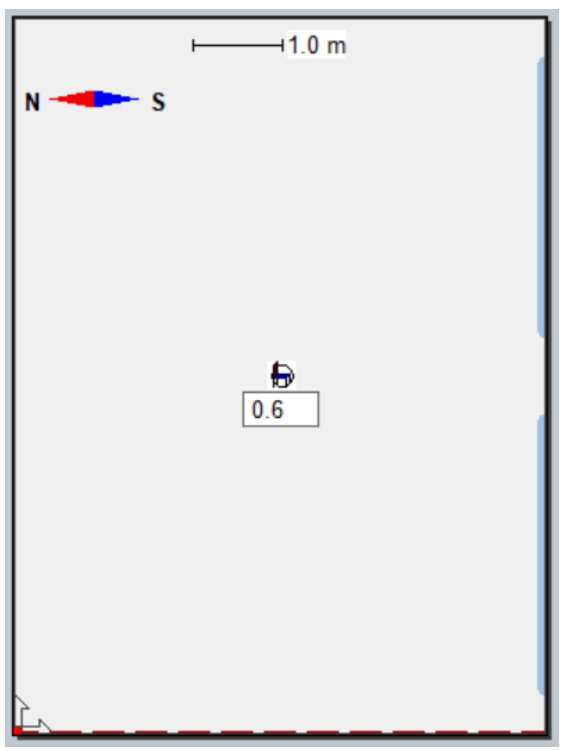

Fig.33. Position of occupant on the floor in the zone.

A.3 Visible solar transmittance (T_{vis}) - Calculations

A limitation to this study is the issue concerning $T_{vis.}$ The fact that IDA ICE does not have a default function for handling smart windows when using the standard window model means that it cannot take into consideration the spectral dependency when a smart window tint. The integrated shading device does not have the input option for a multiplier for T_{vis} and is designed so that the visual spectrum will be decreased with the same factor (multiplier) as the whole spectrum. This means that the software cannot take into account that the optical properties of the smart windows varies depending on the wavelength. This is an important aspect of smart windows, where the intention is to block out heat from solar radiation while still allowing for natural daylight. The software instead uses a fixed parameter called VISGAIN and is calculated by the following equation:

$$VISGAIN = \frac{T_{vis}}{T_{sol}} \tag{4}$$

where T_{vis} and T_{sol} represents the input data for the smart window in its clearest state. This is further used to calculate the daylight level (lux) at a user defined workplane (see Fig. 33) and will have an effect on the following cases:

- ECW “real case” and “real case with same U-value”.
- TCW “real case” and “real case with same U-value”.

The following will be affected:

- Artificial lighting is controlled by the daylighting setpoints, which mean that the energy consumption will have deviations from actual values for both the ECW and the TCW.
- The ECW controlled by daylight is set to maintain a daylight level at 500 lux at a user defined workplane. This daylight level will have deviations from the “real” daylight level the workplane would have had if the ECW was able to change the optical parameters independently. This will further have an indirect impact on the energy consumption.

Apart from this, the energy calculations are not affected since they are only determined by the g-value and T_{sol}. All other simulated cases have the same multiplier for T_{vis} and T_{sol}, which mean that the optical properties change equally in the whole spectrum. To recreate T_{vis}, T_{sol} can be multiplied with VISGAIN. The deviation of the T_{vis} values between using VISGAIN (see Eq.7) and the multiplier for T_{vis} (see Eq.6) will vary depending on the shading signal. This will be explained in more detail in the following. In Table 14 the optical properties for both the ECW and the TCW are presented with associated multipliers and VISGAIN parameter.

Table 14. Optical properties for T_{vis} calculations for the ECW and the TCW. T_{vis} and T_{sol} is presented with associated multipliers and VISGAIN.

Case	Tvis (-)	Multiplier Tvis	Tsol (-)	Multiplier Tsol	VISGAIN
ECW	0.40 - 0.023	0.0575	0.30 - 0.01	0.0333	1.3333
TCW	0.38 - 0.08	0.2105	0.16 - 0.05	0.3125	2.3750

Here it can be seen that the multipliers are different for T_{vis} and T_{sol}, which mean that when the smart windows will tint into darker states, they will change independently. The multipliers are calculated in the same way as the multiplier for the g-value presented previously in "Emulating the tinting of smart windows in IDA ICE" with the following equation:

$$m_{Tvis} = \frac{Tvis_{darkest\ state}}{Tvis_{clearest\ state}} \qquad (5)$$

where

- m_{Tvis} is the multiplier for T_{vis} ranging between 0 and 1.

- $Tvis_{darkest\ state}$ is the T_{vis} at the darkest state of the smart window (-).
- $Tvis_{clearest\ state}$ is the T_{vis} at the clearest state of the smart window (-).

Note that Eq.5 is for the multiplier of T_{vis}, but the same calculation is also valid for the multiplier for T_{sol}.

Together with the actual shading signal, both T_{vis} and T_{sol} of the tinted smart window at any shading state can be calculated by the following equation:

$$T_{vis} = (m_{Tvis} * Tvis_{clearest\ state}) * s + Tvis_{clearest\ state} * (1 - s) \tag{6}$$

where

- T_{vis} is the value of the tinted window at a given shading signal (-).
- m_{Tvis} is the multiplier for the T_{vis} ranging between 0 and 1.
- $Tvis_{clearest\ state}$ is the T_{vis} value at the clearest state of the smart window (-).
- s is the shading signal ranging between 0 and 1, where 0 is equal to no shading and 1 is equal to full shading.

Note that Eq.6 is for T_{vis}, but the same calculation is also valid for $T_{sol.}$

However, instead of using Eq.6, IDA ICE calculates T_{vis} by the following equation:

$$Tvis = VISGAIN * Tsol \tag{7}$$

Table 15 and Figure 34 show the tinted values for T_{vis} and the deviation between the real value obtained by using the multiplier for T_{vis} and how IDA ICE does it by using the VISGAIN parameter for the ECW.

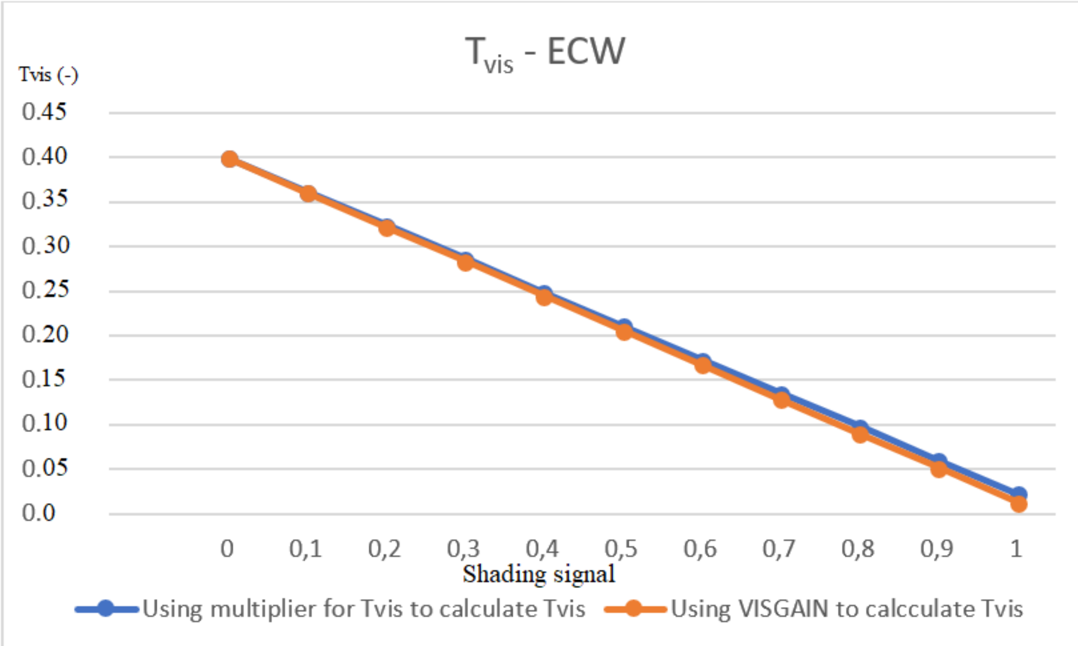

Fig.34. T_{vis} calculations for ECW. The figure shows the shading signal and associated values for T_{vis} using the multiplier for T_{vis} and T_{vis} using the VISGAIN parameter.

Table 15. T_{vis} calculations for ECW. The table shows the shading signal and associated values for T_{vis} using the multiplier for T_{vis}, T_{sol} using the multiplier for T_{sol}, T_{vis} using the VISGAIN parameter and the deviation between T_{vis} values.

S-signal	Using multiplier for Tvis to calculate Tvis	Using multiplier for Tsol to calculate Tsol	Using VISGAIN to calcculate Tvis	Deviation between Tvis
0	0.400	0.30	0.400	0.00001
0.1	0.362	0.27	0.361	0.00098
0.2	0.325	0.24	0.323	0.00194
0.3	0.287	0.21	0.284	0.00291
0.4	0.249	0.18	0.245	0.00388
0.5	0.212	0.15	0.207	0.00485
0.6	0.174	0.13	0.168	0.00581
0.7	0.136	0.10	0.129	0.00678
0.8	0.098	0.07	0.091	0.00775
0.9	0.061	0.04	0.052	0.00871
1	0.023	0.01	0.013	0.00968

Here it can be seen that the deviation between using the multiplier for T_{vis} and the VISGAIN parameter becomes larger as the window tint with a maximum deviation of approximately 43 % (0.00968) at a shading signal equal 1.

Table 16 and Figure 35 show the values for T_{vis} and the deviation when using the multiplier for T_{vis} and the VISGAIN parameter for TCW.

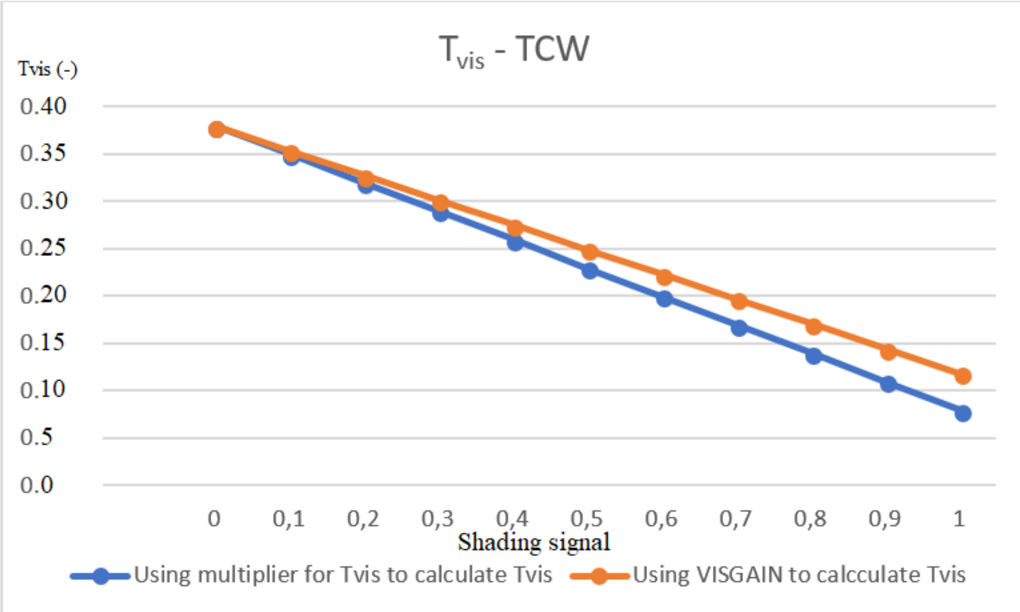

Fig.35. T_{vis} calculations for TCW.The figure shows the shading signal and associated values for T_{vis} using the multiplier for T_{vis} and T_{vis} using the VISGAIN parameter.

Table 16. T_{vis} calculations for TCW.The table shows the shading signal and associated values for T_{vis} using the multiplier for T_{vis}, T_{sol} using the multiplier for T_{sol}, T_{vis} using the VISGAIN parameter and the deviation between T_{vis} values.

S-signal	Using multiplier for Tvis to calculate Tvis	Using multiplier for Tsol to calculate Tsol	Using VISGAIN to calcculate Tvis	Deviation between Tvis
0	0.380	0.16	0.38	0.000
0.1	0.350	0.149	0.353875	0.004
0.2	0.320	0.138	0.32775	0.008
0.3	0.290	0.127	0.301625	0.012
0.4	0.260	0.116	0.2755	0.016
0.5	0.230	0.105	0.249375	0.019
0.6	0.200	0.094	0.22325	0.023
0.7	0.170	0.083	0.197125	0.027
0.8	0.140	0.072	0.171	0.031
0.9	0.110	0.061	0.144875	0.035
1	0.080	0.05	0.11875	0.039

Here it can be seen that the deviation between using the multiplier for T_{vis} and the VISGAIN parameter becomes larger as the window tint with a maximum deviation of approximately 50 % (0.039) at a shading signal equal 1. Note that T_{vis}, when using the multiplier for T_{vis}, for the ECW deviates to lower values while the TCW deviates to higher values compared to when the VISGAIN parameter is used.

A.4 Results

A.4.1 Delivered energy Trondheim, Norway

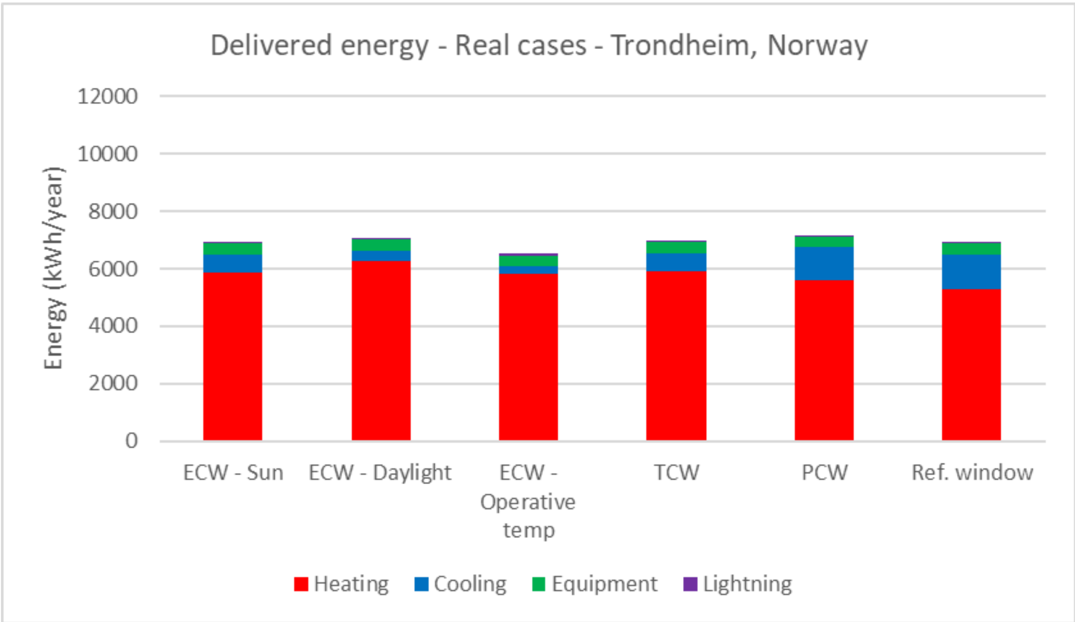

Fig.36. Delivered energy for real cases in Trondheim, Norway. Each column is divided into heating, cooling, equipment and lighting, where the height of the columns represent the total delivered energy in kWh/year.

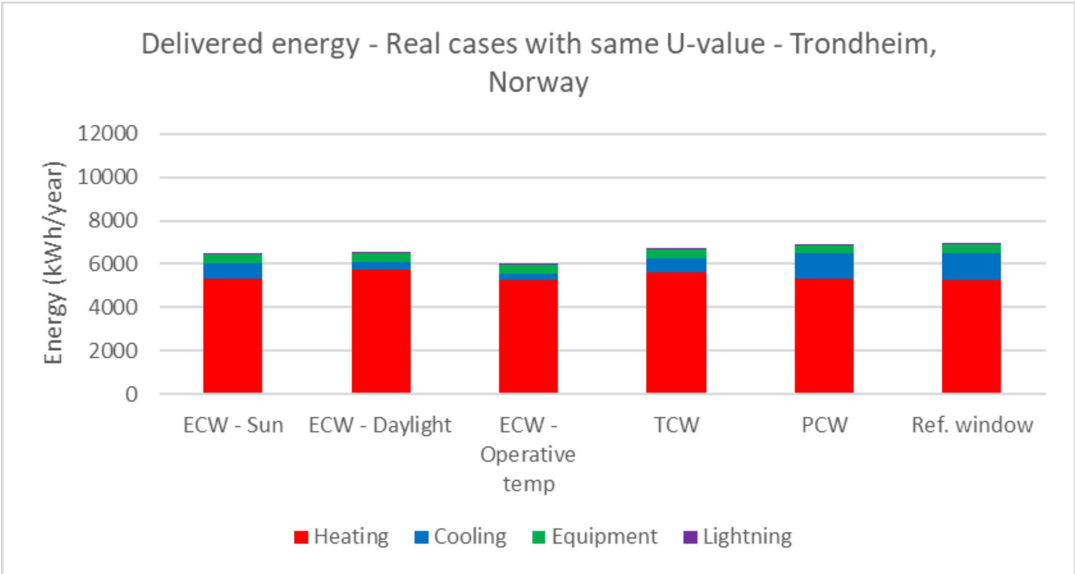

Fig.37. Delivered energy for real cases with same U-value in Trondheim, Norway. Each column is divided into heating, cooling, equipment and lighting, where the height of the columns represent the total delivered energy in kWh/year.

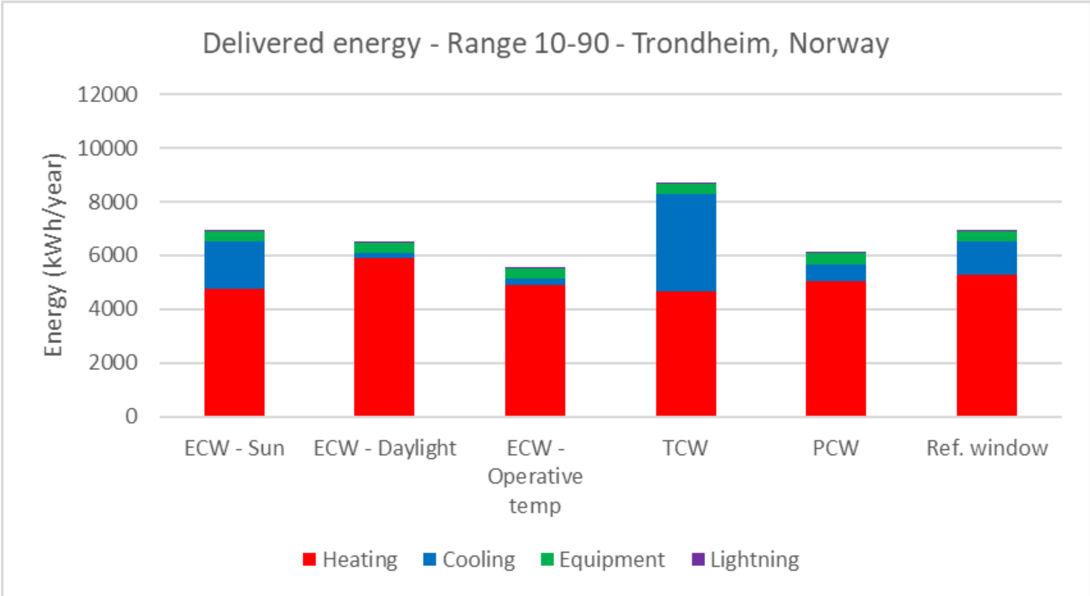

Fig.38. Delivered energy for Range 10-90 in Trondheim, Norway. Each column is divided into heating, cooling, equipment and lighting, where the height of the columns represent the total delivered energy in kWh/year.

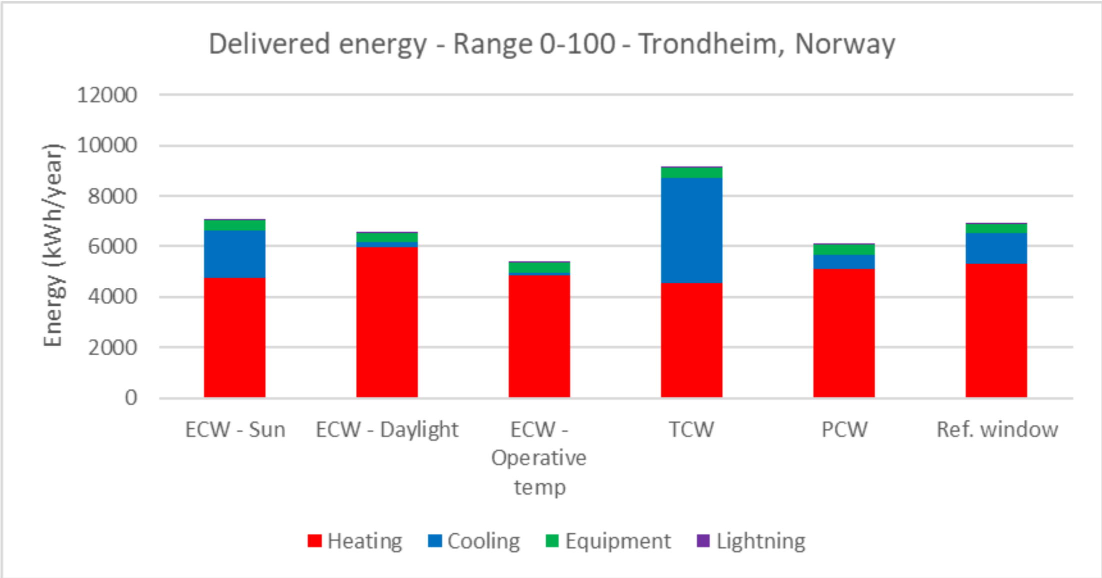

Fig.39. Delivered energy for Range 0-100 in Trondheim, Norway. Each column is divided into heating, cooling, equipment and lighting, where the height of the columns represent the total delivered energy in kWh/year.

Table 17. Delivered energy for all cases in Trondheim, Norway. Total delivered energy is divided into heating, cooling, equipment and lighting.

		Case	Manufacturer	Product	Heating (kWh/year)	Cooling (kWh/year)	Equipment (kWh/year)	Lighting (kWh/year)	Total (kWh/year)
Real cases	Adaptive	TCW	Pleotint LLC	Solarblue	5917	633	392	31	6973
Real cases	Adaptive	PCW	Chameleon	Chameleon 53	5578	1156	392	27	7153
Real cases	Controllable	ECW - Sun	SAGE Electrochromics	Cool View Blue	5856	651	392	54	6953
Real cases	Controllable	ECW - Operative temperature	SAGE Electrochromics	Cool View Blue	5815	253	392	65	6524
Real cases	Controllable	ECW - Daylight	SAGE Electrochromics	Cool View Blue	6284	359	392	30	7065
Real cases with same U-value	Adaptive	TCW	Pleotint LLC	Solarblue	5618	660	392	31	6700
Real cases with same U-value	Adaptive	PCW	Chameleon	Chameleon 53	5299	1184	392	27	6901
Real cases with same U-value	Controllable	ECW - Sun	SAGE Electrochromics	Cool View Blue	5312	709	392	54	6466
Real cases with same U-value	Controllable	ECW - Operative temperature	SAGE Electrochromics	Cool View Blue	5291	273	392	67	6022
Real cases with same U-value	Controllable	ECW - Daylight	SAGE Electrochromics	Cool View Blue	5714	391	392	30	6527
Range 10-90	Adaptive	TCW	N/A[1]	N/A[1]	4643	3631	392	22	8687
Range 10-90	Adaptive	PCW	N/A[1]	N/A[1]	5049	629	392	22	6091
Range 10-90	Controllable	ECW - Sun	N/A[1]	N/A[1]	4775	1737	392	22	6926
Range 10-90	Controllable	ECW - Operative temperature	N/A[1]	N/A[1]	4887	261	392	26	5566
Range 10-90	Controllable	ECW - Daylight	N/A[1]	N/A[1]	5887	217	392	22	6518
Range 0-100	Adaptive	TCW	N/A[1]	N/A[1]	4559	4165	392	22	9138
Range 0-100	Adaptive	PCW	N/A[1]	N/A[1]	5125	530	392	49	6095
Range 0-100	Controllable	ECW - Sun	N/A[1]	N/A[1]	4763	1890	392	45	7089
Range 0-100	Controllable	ECW - Operative temperature	N/A[1]	N/A[1]	4836	109	392	54	5391
Range 0-100	Controllable	ECW - Daylight	N/A[1]	N/A[1]	5952	208	392	22	6572
		Reference window	Saint-Gobain	Cool-Lite 174+ar	5290	1217	392	24	6922

[1] Non-applicaple. Range 10-90 and Range 0-100 cases does not apply to any real product.

A.4.2 Delivered energy Madrid, Spain

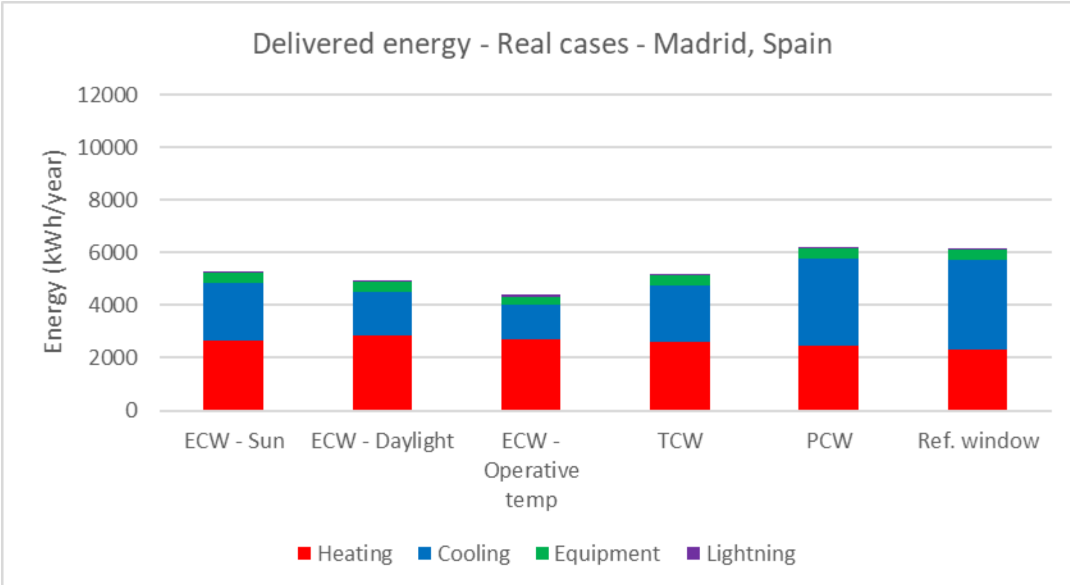

Fig.40. Delivered energy for real cases in Madrid, Spain. Each column is divided into heating, cooling, equipment and lighting, where the height of the columns represent the total delivered energy in kWh/year.

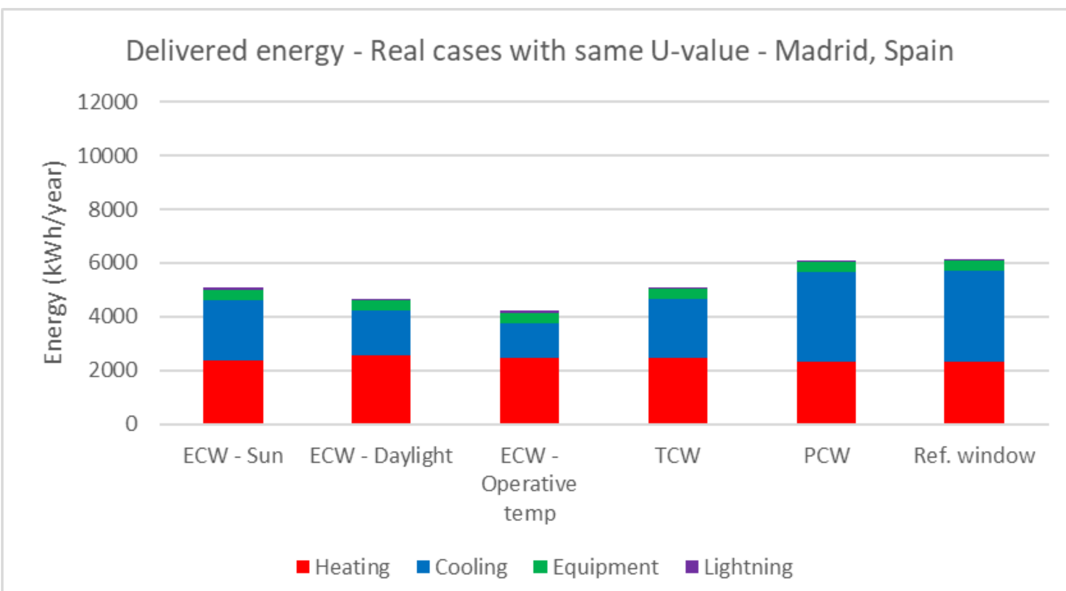

Fig.41. Delivered energy for real cases with same U-value in Madrid, Spain. Each column is divided into heating, cooling, equipment and lighting, where the height of the columns represent the total delivered energy in kWh/year.

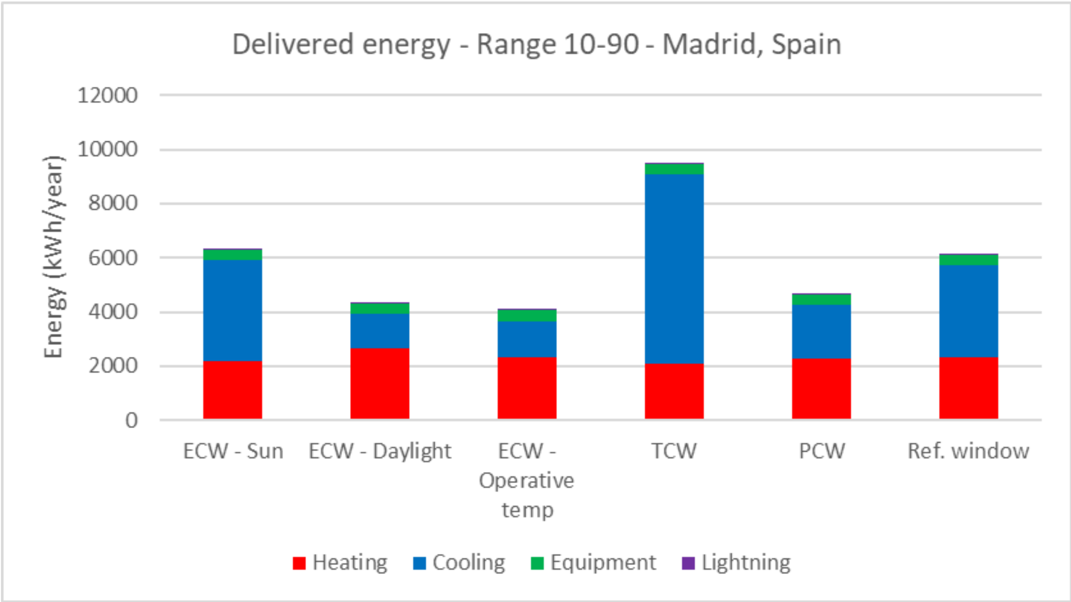

Fig.42. Delivered energy for Range 10-90 in Madrid, Spain. Each column is divided into heating, cooling, equipment and lighting, where the height of the columns represent the total delivered energy in kWh/year.

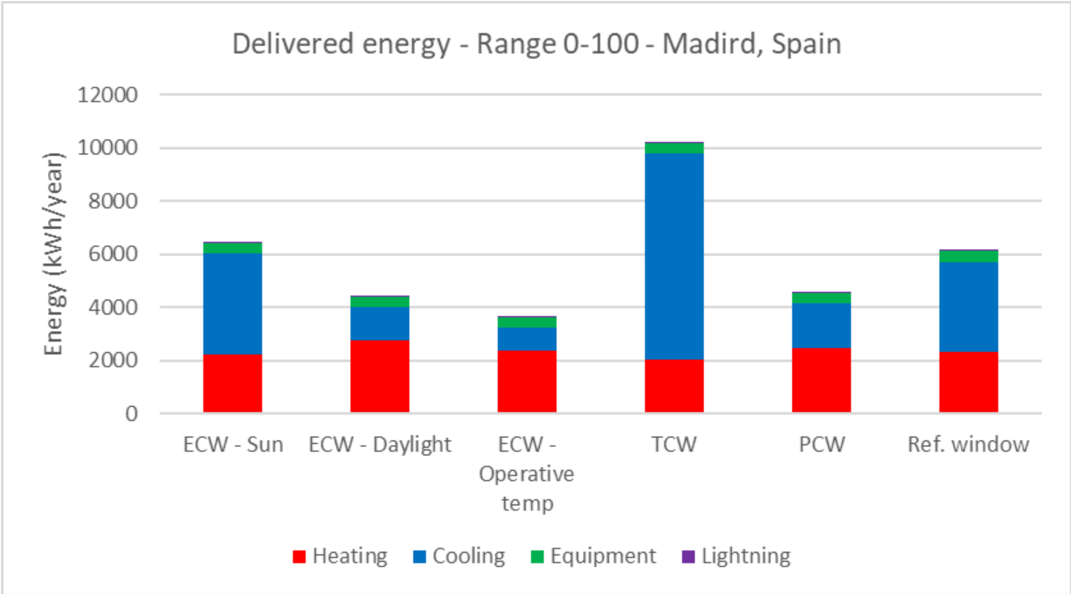

Fig.43. Delivered energy for Range 0-100 in Madrid, Spain. Each column is divided into heating, cooling, equipment and lighting where the height of the columns represents the total delivered energy in kWh/year.

Table 18. Delivered energy for all cases in Madrid, Spain. Total delivered energy is divided into heating, cooling, equipment and lighting.

		Case	Manufacturer	Product	Heating (kWh/year)	Cooling (kWh/year)	Equipment (kWh/year)	Lighting (kWh/year)	Total (kWh/year)
Real cases	Adaptive	TCW	Pleotint LLC	Solarblue	2606	2158	392	22	5177
		PCW	Chameleon	Chameleon 53	2472	3311	392	19	6194
	Controllable	ECW - Sun	SAGE Electrochromics	Cool View Blue	2642	2209	392	61	5303
		ECW - Operative temperature	SAGE Electrochromics	Cool View Blue	2706	1304	320	89	4419
		ECW - Daylight	SAGE Electrochromics	Cool View Blue	2833	1658	392	22	4904
Real cases with same U-value	Adaptive	TCW	Pleotint LLC	Solarblue	2458	2188	392	22	5060
		PCW	Chameleon	Chameleon 53	2333	3334	392	19	6077
	Controllable	ECW - Sun	SAGE Electrochromics	Cool View Blue	2373	2245	392	61	5071
		ECW - Operative temperature	SAGE Electrochromics	Cool View Blue	2444	1322	392	90	4248
		ECW - Daylight	SAGE Electrochromics	Cool View Blue	2540	1686	392	22	4640
Range 10-90	Adaptive	TCW	N/A[1]	N/A[1]	2071	7014	392	15	9492
		PCW	N/A[1]	N/A[1]	2297	1956	392	15	4659
	Controllable	ECW - Sun	N/A[1]	N/A[1]	2168	3749	392	15	6323
		ECW - Operative temperature	N/A[1]	N/A[1]	2345	1318	392	22	4076
		ECW - Daylight	N/A[1]	N/A[1]	2661	1260	392	15	4327
Range 0-100	Adaptive	TCW	N/A[1]	N/A[1]	2041	7739	392	14	10186
		PCW	N/A[1]	N/A[1]	2469	1675	392	63	4599
	Controllable	ECW - Sun	N/A[1]	N/A[1]	2469	1675	392	63	4599
		ECW - Operative temperature	N/A[1]	N/A[1]	2365	858	392	76	3690
		ECW - Daylight	N/A[1]	N/A[1]	2773	1237	392	14	4415
		Reference window	Saint-Gobain	Cool-Lite 174+ar	2313	3401	392	17	6122

[1] Non-applicapble. Range 10-90 and Range 0-100 cases does not apply to any real product.

A.4.3 Delivered energy Nairobi, Kenya

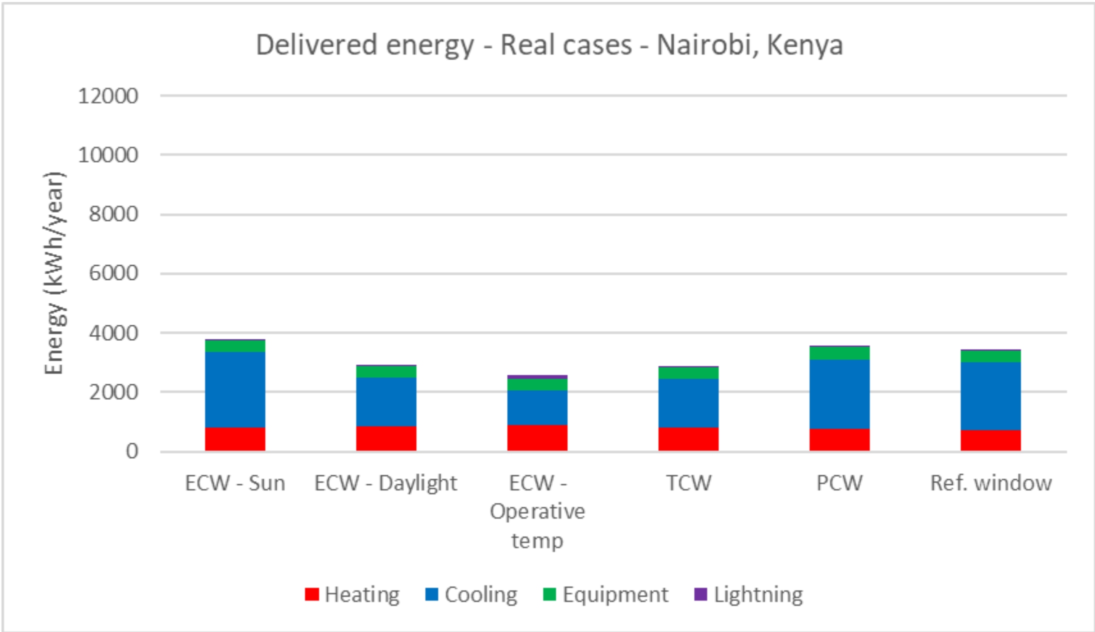

Fig.44. Delivered energy for real cases in Nairobi, Kenya. Each column is divided into heating, cooling, equipment and lighting, where the height of the columns represent the total delivered energy in kWh/year.

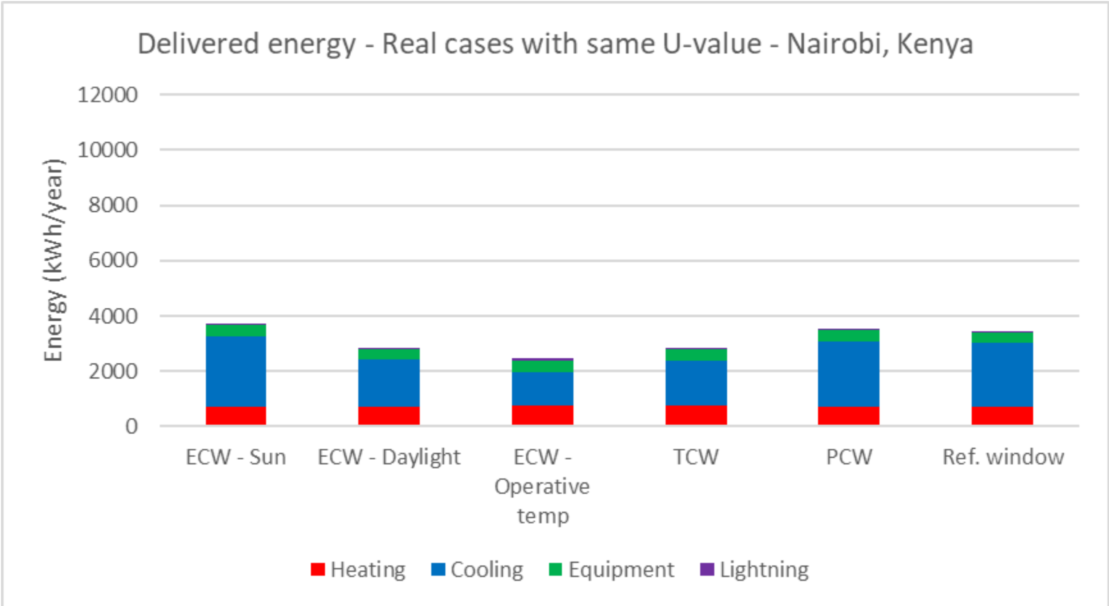

Fig.45. Delivered energy for real cases with same U-value in Nairobi, Kenya. Each column is divided into heating, cooling, equipment and lighting, where the height of the columns represent the total delivered energy in kWh/year.

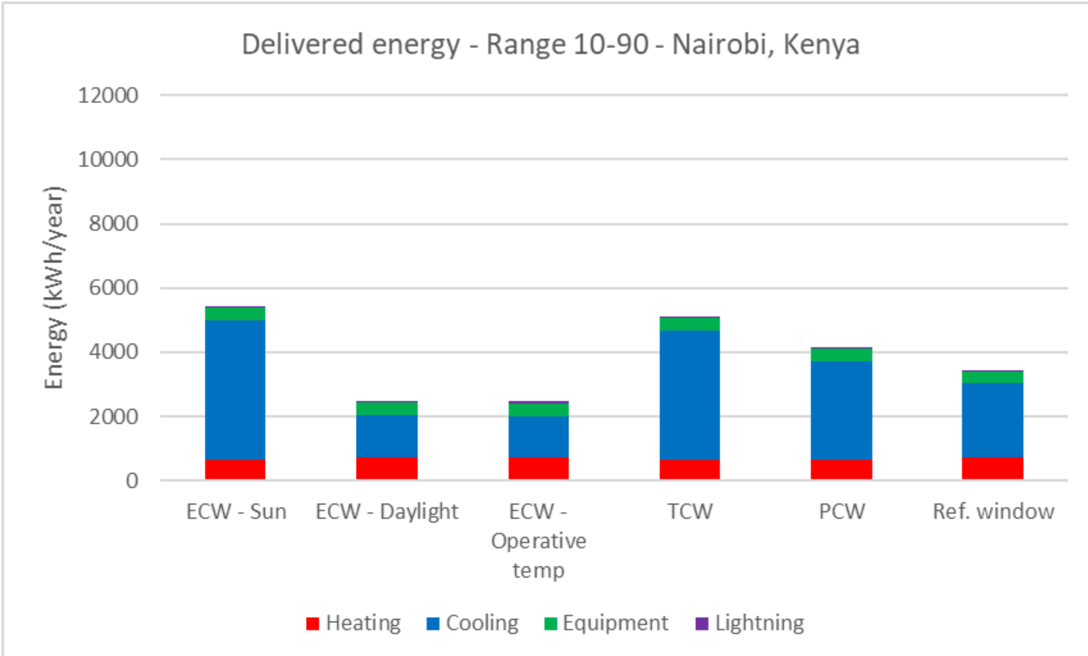

Fig.46. Delivered energy for Range 10-90 in Nairobi, Kenya. Each column is divided into heating, cooling, equipment and lighting, where the height of the columns represent the total delivered energy in kWh/year.

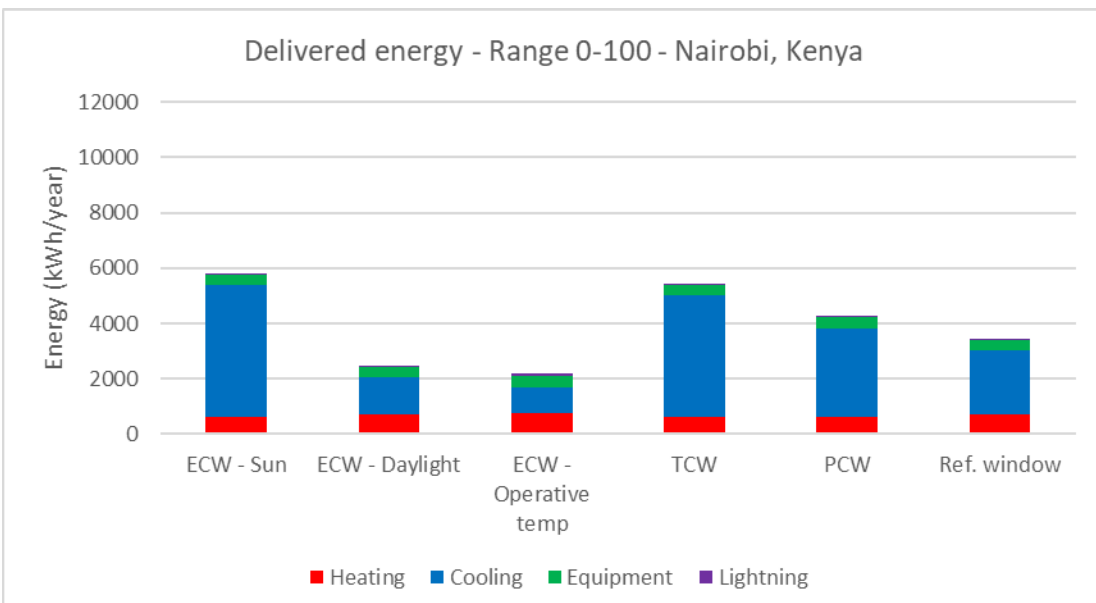

Fig.47. Delivered energy for Range 0-100 in Nairobi, Kenya. Each column is divided into heating, cooling, equipment and lighting, where the height of the columns represent the total delivered energy in kWh/year.

Table 19. Delivered energy for all cases in Nairobi, Kenya. Total delivered energy is divided into heating, cooling, equipment and lighting.

		Case	Manufacturer	Product	Heating (kWh/year)	Cooling (kWh/year)	Equipment (kWh/year)	Lighting (kWh/year)	Total (kWh/year)
Real cases	Adaptive	TCW	Pleotint LLC	Solarblue	813	1615	392	15	2834
		PCW	Chameleon	Chameleon 53	771	2347	392	12	3521
	Controllable	ECW - Sun	SAGE Electrochromics	Cool View Blue	809	2534	392	16	3751
		ECW - Operative temperature	SAGE Electrochromics	Cool View Blue	876	1201	392	96	2564
		ECW - Daylight	SAGE Electrochromics	Cool View Blue	837	1646	392	14	2889
Real cases with same U-value	Adaptive	TCW	Pleotint LLC	Solarblue	749	1639	392	15	2795
		PCW	Chameleon	Chameleon 53	711	2370	392	12	3483
	Controllable	ECW - Sun	SAGE Electrochromics	Cool View Blue	693	2585	392	16	3686
		ECW - Operative temperature	SAGE Electrochromics	Cool View Blue	758	1231	392	97	2477
		ECW - Daylight	SAGE Electrochromics	Cool View Blue	722	1690	392	14	2817
Range 10-90	Adaptive	TCW	N/A[1]	N/A[1]	634	4043	392	8	5076
		PCW	N/A[1]	N/A[1]	639	3084	392	8	4123
	Controllable	ECW - Sun	N/A[1]	N/A[1]	624	4362	392	8	5385
		ECW - Operative temperature	N/A[1]	N/A[1]	729	1290	392	50	2460
		ECW - Daylight	N/A[1]	N/A[1]	717	1314	392	8	2430
Range 0-100	Adaptive	TCW	N/A[1]	N/A[1]	625	4374	392	8	5399
		PCW	N/A[1]	N/A[1]	625	4374	392	8	5399
	Controllable	ECW - Sun	N/A[1]	N/A[1]	612	4780	392	9	5793
		ECW - Operative temperature	N/A[1]	N/A[1]	749	950	392	98	2188
		ECW - Daylight	N/A[1]	N/A[1]	711	1339	392	7	2449
		Reference window	Saint-Gobain	Cool-Lite 174+ar	708	2311	392	9	3419

[1] Non-applicaple. Range 10-90 and Range 0-100 cases does not apply to any real product.

A.4.4 Energy balance Trondheim, Norway

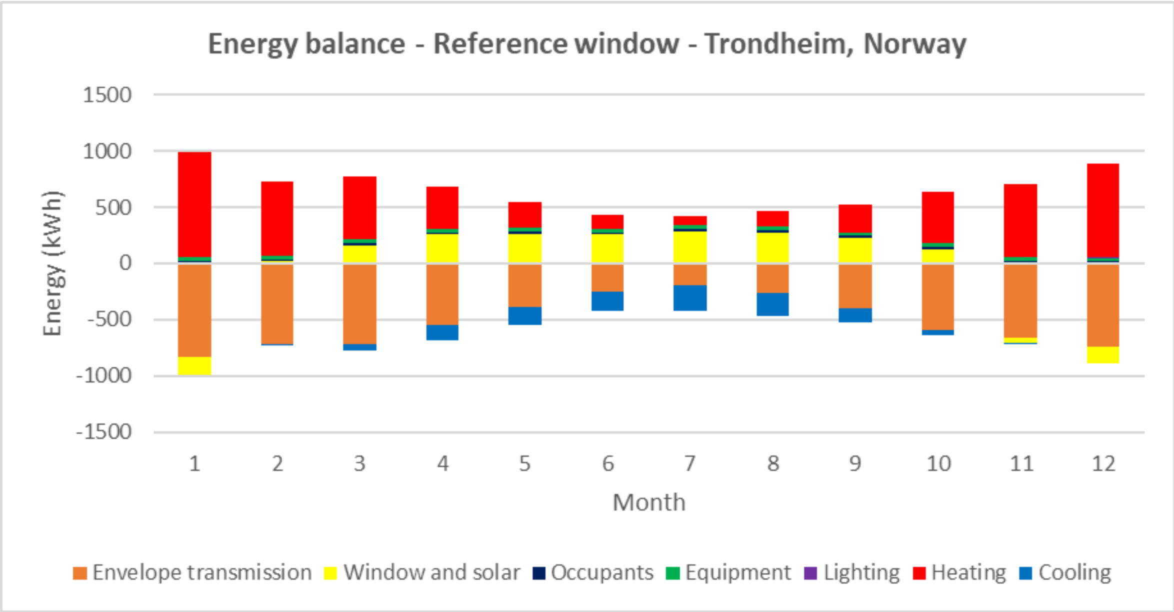

Fig.48. Energy balance - Reference window - Trondheim, Norway. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 20. Energy balance - Reference window - Trondheim, Norway. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - Reference window - Trondheim, Norway (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-834	-151	19	35	6	926	0
2	-716	19	17	30	2	658	-9
3	-721	159	18	33	1	564	-53
4	-543	260	17	32	0	379	-144
5	-386	265	18	35	0	234	-165
6	-253	260	16	32	0	118	-174
7	-192	286	17	33	0	80	-225
8	-260	278	18	35	0	136	-207
9	-401	229	16	30	1	252	-127
10	-591	130	19	35	2	456	-49
11	-659	-48	18	33	5	652	-1
12	-738	-154	18	32	8	835	0
Total	**-6295**	**1534**	**210**	**392**	**24**	**5290**	**-1153**
During heating (6291.9 h)	-5008	-635	114	209	24	5289	0
During cooling (1872.3 h)	-960	1896	77	147	0	0	-1153
Rest of time	-326	273	19	36	0	1	0

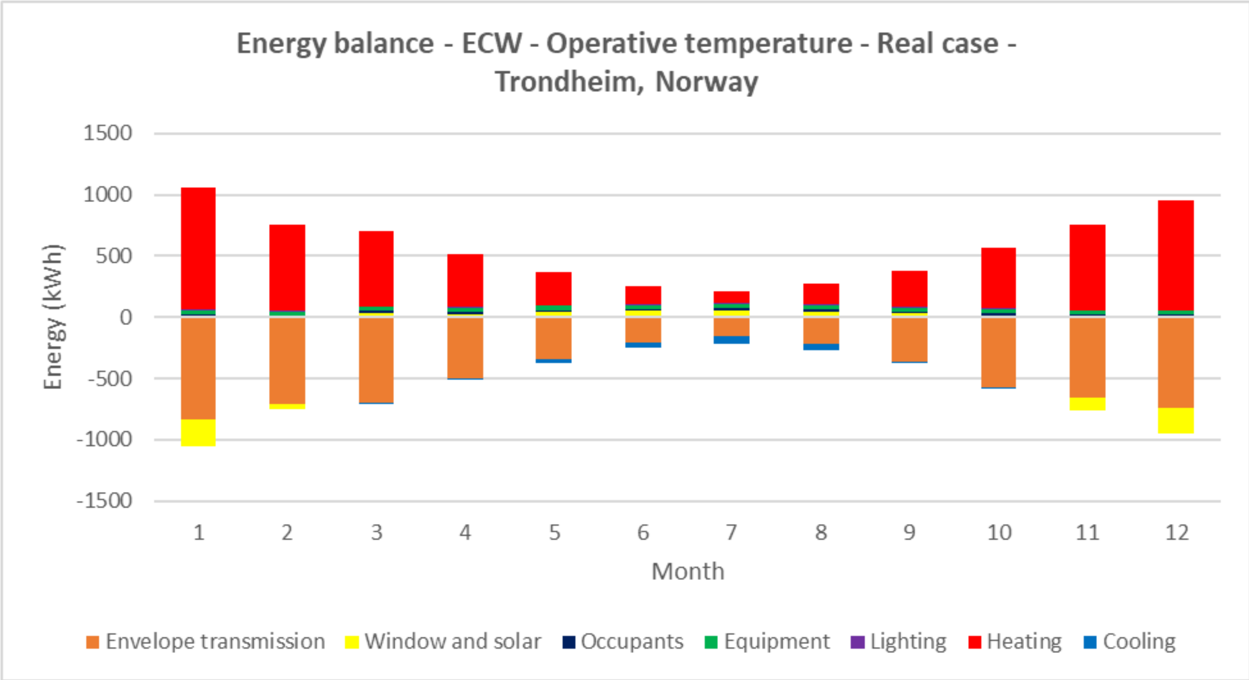

Fig.49. Energy balance - ECW - Operative temperature - Real case - Trondheim, Norway. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 21. Energy balance - ECW - Operative temperature - Real case - Trondheim, Norway. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - ECW - Operative temperature - Real case - Trondheim, Norway (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-833	-220	19	35	7	992	0
2	-710	-46	17	30	3	707	0
3	-701	33	19	33	2	615	0
4	-502	28	18	32	4	430	-8
5	-345	40	19	35	6	272	-27
6	-212	51	17	32	6	145	-38
7	-152	58	17	33	7	100	-65
8	-221	47	18	35	7	163	-50
9	-363	31	16	30	6	295	-14
10	-569	14	20	35	3	501	-2
11	-656	-101	18	33	5	700	0
12	-736	-218	18	32	8	896	0
Total	**-6000**	**-284**	**216**	**392**	**65**	**5815**	**-203**
During heating (6391.4 h)	-5028	-1136	112	202	30	5814	0
During cooling (1557.8 h)	-556	496	82	150	35	0	-202
Rest of time	-417	357	22	39	0	1	0

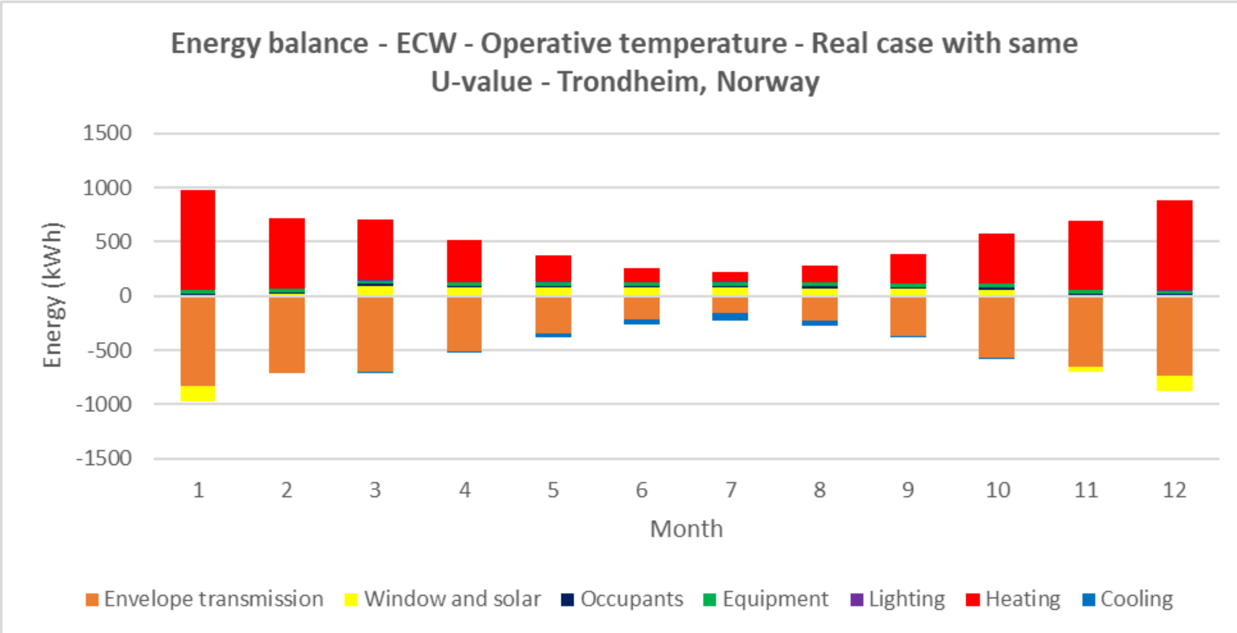

Fig.50. Energy balance - ECW - Operative temp - Real case with same U-value - Trondheim.Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 22. Energy balance - ECW - Operative temp - Real case with same U-value - Trondheim.Each category is presented per month and during heating, cooling and rest of time.

Energy balance - ECW - Operative temperature - Real case with same U-value - Trondheim, Norway (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-834	-139	19	35	7	912	0
2	-712	19	17	30	3	644	0
3	-704	92	19	33	2	559	0
4	-506	75	18	32	5	389	-11
5	-349	76	19	35	7	243	-30
6	-216	76	17	32	7	126	-41
7	-156	79	17	33	7	86	-69
8	-224	72	18	35	7	145	-53
9	-366	64	16	30	6	266	-16
10	-572	61	20	35	4	456	-2
11	-658	-39	18	33	5	640	0
12	-737	-146	18	32	8	825	0
Total	**-6032**	**289**	**215**	**392**	**67**	**5291**	**-222**
During heating (6273.0 h)	-4972	-659	108	195	30	5292	0
During cooling (1661.0 h)	-622	568	86	158	36	0	-222
Rest of time	-438	380	21	39	0	0	0

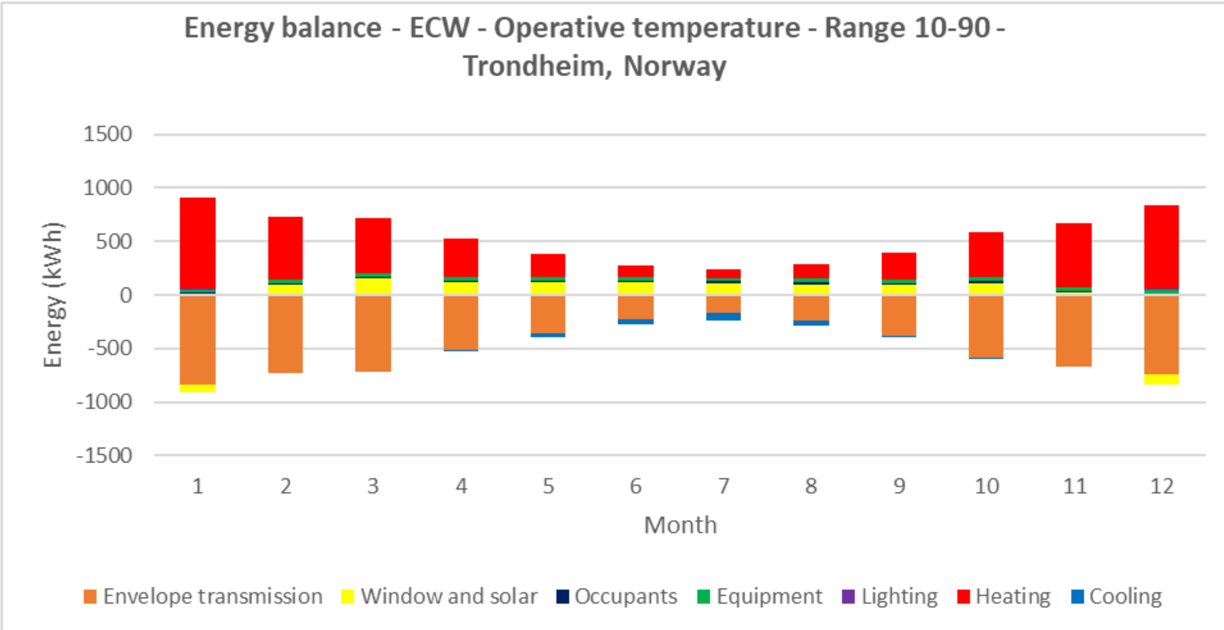

Fig.51. Energy balance - ECW - Operative temperature - Range - 10-90 - Trondheim, Norway. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 23. Energy balance - ECW - Operative temperature - Range 10-90 - Trondheim, Norway. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - ECW - Operative temperature - Range 10-90 - Trondheim, Norway (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-839	-72	19	35	6	851	0
2	-726	96	17	30	2	582	0
3	-721	154	19	33	0	514	0
4	-519	118	18	32	0	361	-10
5	-362	119	19	35	0	217	-28
6	-230	115	17	32	1	106	-41
7	-170	110	17	33	1	74	-68
8	-235	99	18	35	1	133	-51
9	-377	92	16	30	1	252	-15
10	-586	113	20	35	2	420	-2
11	-668	20	19	33	4	593	0
12	-741	-100	18	32	7	785	0
Total	**-6174**	**863**	**216**	**392**	**26**	**4888**	**-213**
During heating (5748 h)	-4642	-511	84	152	22	4886	0
During cooling (1968.2 h)	-855	761	109	197	4	0	-213
Rest of time	-677	613	24	43	1	1	0

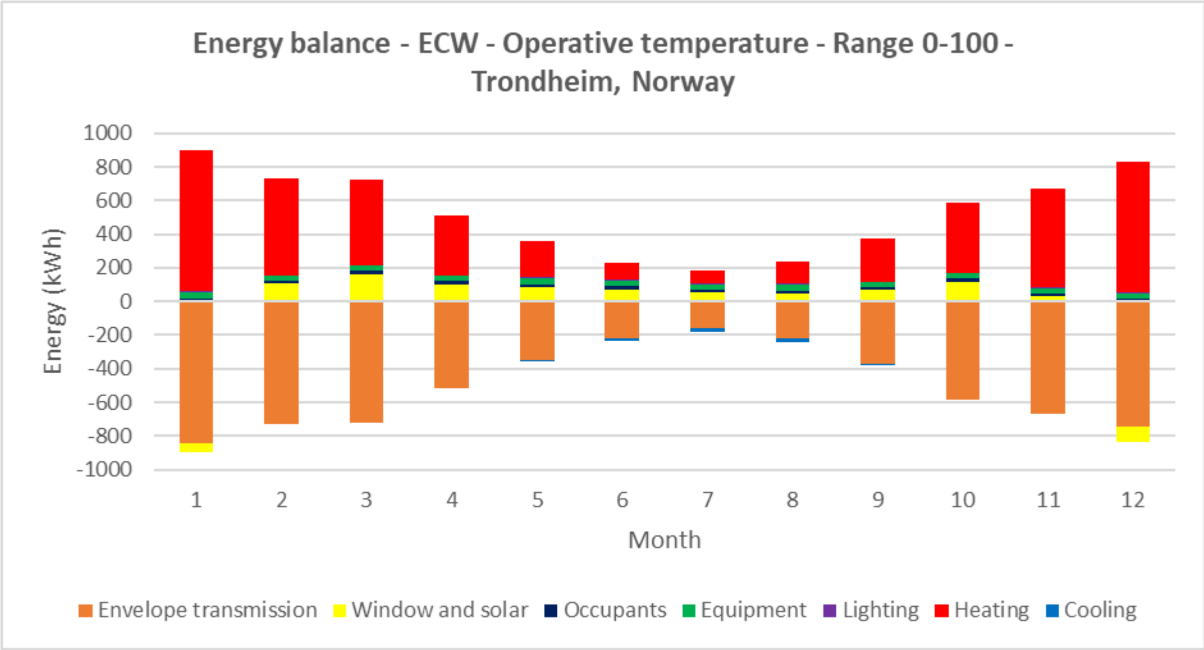

Fig.52. Energy balance - ECW - Operative temperature - Range 0-100 - Trondheim, Norway. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 24. Energy balance - ECW - Operative temperature - Range 0-100 - Trondheim, Norway. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - ECW - Operative temperature - Range 0-100 - Trondheim, Norway (kWh)							
Month	**Envelope transmission**	**Window and solar**	**Occupants**	**Equipment**	**Lighting**	**Heating**	**Cooling**
1	-841	-58	19	35	6	839	0
2	-729	104	17	30	2	575	0
3	-723	162	19	33	0	509	0
4	-513	103	18	32	2	358	0
5	-352	83	20	35	6	214	-6
6	-219	73	18	32	6	105	-14
7	-156	52	18	33	8	74	-29
8	-221	46	19	35	7	135	-20
9	-369	68	17	30	4	251	-2
10	-587	115	20	35	2	416	0
11	-669	29	19	33	4	585	0
12	-743	-91	18	32	7	777	0
Total	**-6120**	**686**	**220**	**392**	**54**	**4836**	**-71**
During heating (5684.6 h)	-4586	-506	80	144	21	4836	0
During cooling (1799.8 h)	-789	511	116	204	32	0	-71
Rest of time	-745	681	24	43	1	0	0

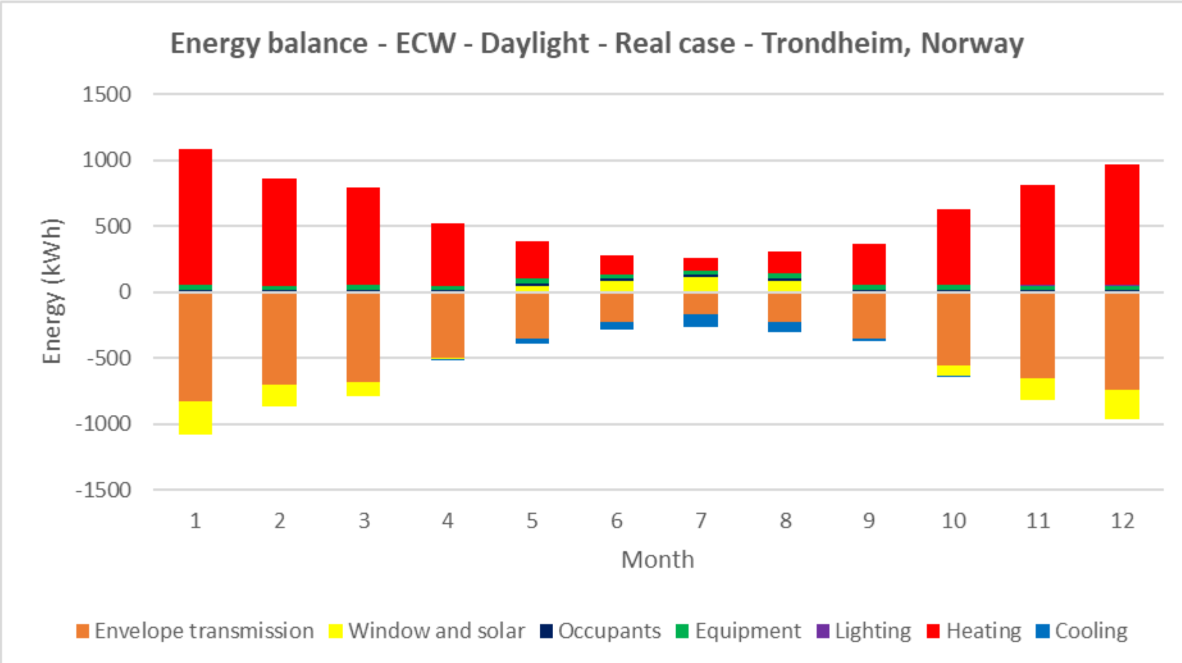

Fig.53. Energy balance - ECW - Daylight - Real case - Trondheim, Norway. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 25. Energy balance - ECW - Daylight - Real case - Trondheim, Norway. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - ECW - Daylight - Real case - Trondheim, Norway (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-831	-250	19	35	7	1020	0
2	-701	-161	17	30	3	813	0
3	-678	-111	18	33	1	738	0
4	-495	-12	18	32	1	469	-12
5	-347	51	18	35	0	284	-42
6	-221	89	17	32	0	145	-62
7	-164	116	17	33	0	98	-101
8	-228	89	18	35	1	162	-77
9	-354	6	16	30	1	315	-15
10	-553	-79	19	35	2	577	-1
11	-651	-162	18	33	5	756	0
12	-736	-229	18	32	8	908	0
Total	**-5958**	**-654**	**214**	**392**	**30**	**6284**	**-309**
During heating (7020.6 h)	-5503	-1227	147	266	30	6283	0
During cooling (1157.7 h)	-281	455	48	90	0	0	-309
Rest of time	-174	118	19	35	0	1	0

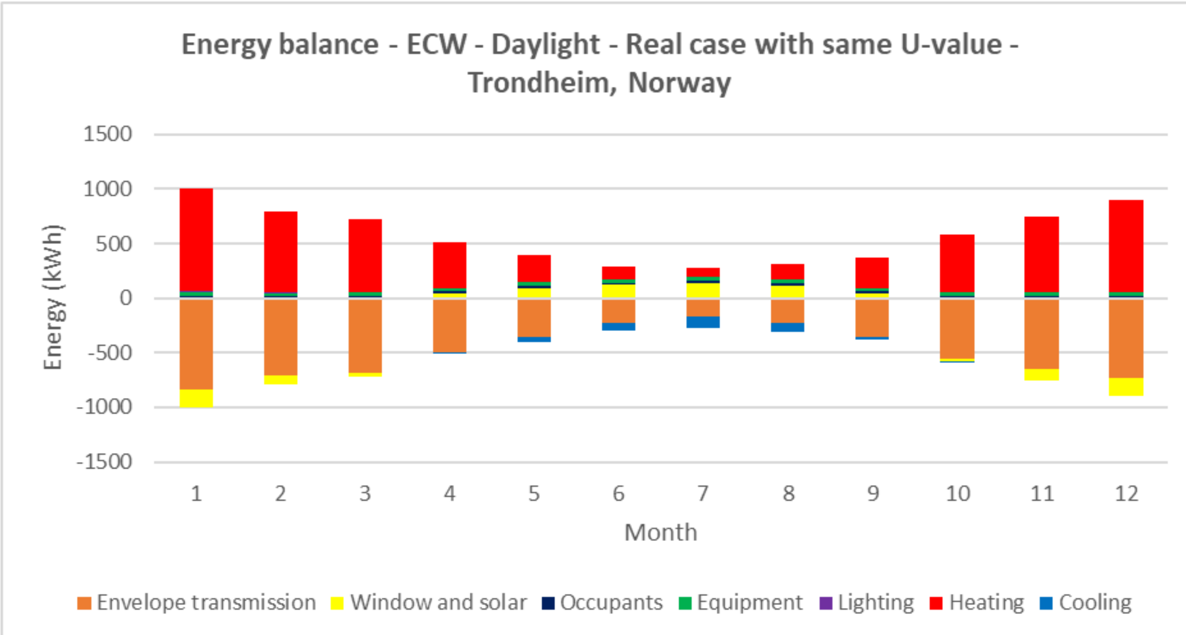

Fig.54. Energy balance - ECW - Daylight - Real case with same U-value - Trondheim, Norway. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 26. Energy balance - ECW - Daylight - Real case with same U-value - Trondheim, Norway. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - ECW - Daylight - Real case with same U-value - Trondheim, Norway (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-832	-169	19	35	7	940	0
2	-702	-92	17	30	3	745	0
3	-680	-41	18	33	1	669	0
4	-499	44	18	32	1	420	-15
5	-352	95	18	35	0	251	-48
6	-226	122	17	32	0	125	-69
7	-169	142	17	33	0	83	-107
8	-232	118	18	35	1	143	-83
9	-357	44	16	30	1	283	-17
10	-555	-24	19	35	2	525	-1
11	-652	-98	18	33	5	693	0
12	-737	-158	18	32	8	837	0
Total	**-5992**	**-17**	**214**	**392**	**30**	**5714**	**-340**
During heating (6874.9 h)	-5458	-688	141	257	30	5714	0
During cooling (1249.3 h)	-324	521	51	96	0	0	-341
Rest of time	-210	149	21	39	0	0	0

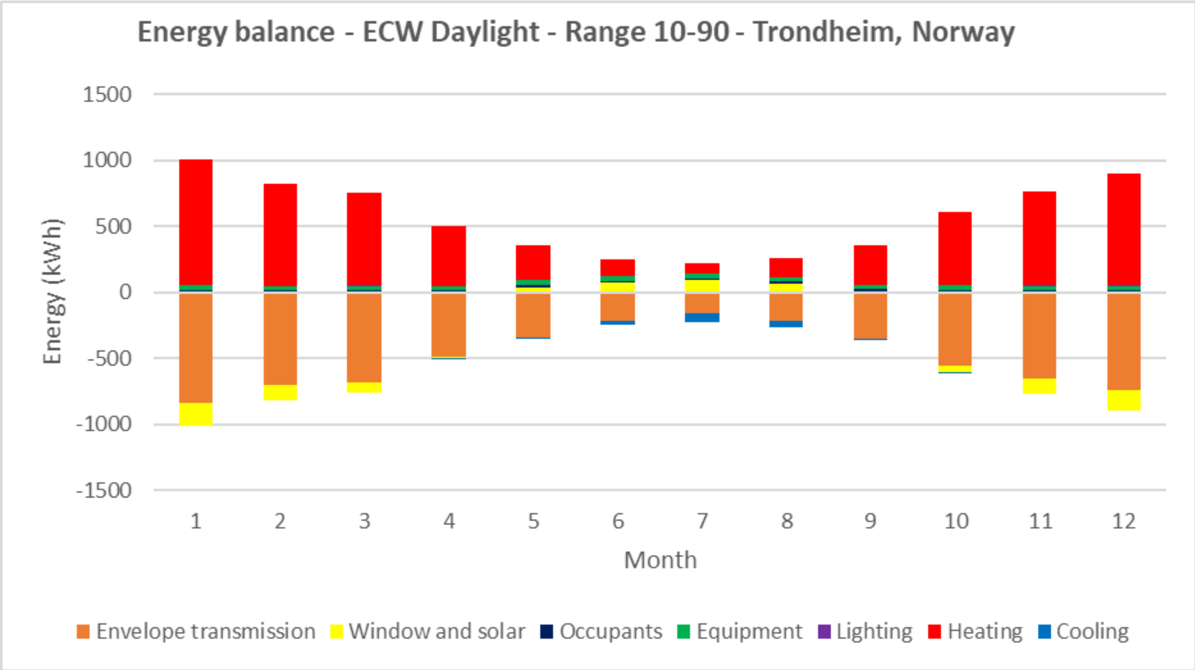

Fig.55. Energy balance - ECW - Daylight - Range 10-90 - Trondheim, Norway. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 27. Energy balance - ECW - Daylight - Range 10-90 - Trondheim, Norway. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - ECW - Daylight - Range 10-90 - Trondheim, Norway (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-833	-174	19	35	6	947	0
2	-703	-116	17	30	2	770	0
3	-680	-75	18	33	0	703	0
4	-487	-9	18	32	0	449	-2
5	-338	38	19	35	0	264	-18
6	-213	72	17	32	0	128	-35
7	-158	91	17	33	0	81	-65
8	-220	64	18	35	0	147	-45
9	-350	12	17	30	1	298	-8
10	-553	-53	19	35	2	551	-1
11	-652	-113	18	33	4	710	0
12	-737	-159	18	32	7	841	0
Total	**-5923**	**-421**	**215**	**392**	**22**	**5887**	**-172**
During heating (7195.5 h)	-5600	-747	155	281	22	5886	0
During cooling (920.1 h)	-152	222	36	67	0	0	-172
Rest of time	-171	104	24	44	0	1	0

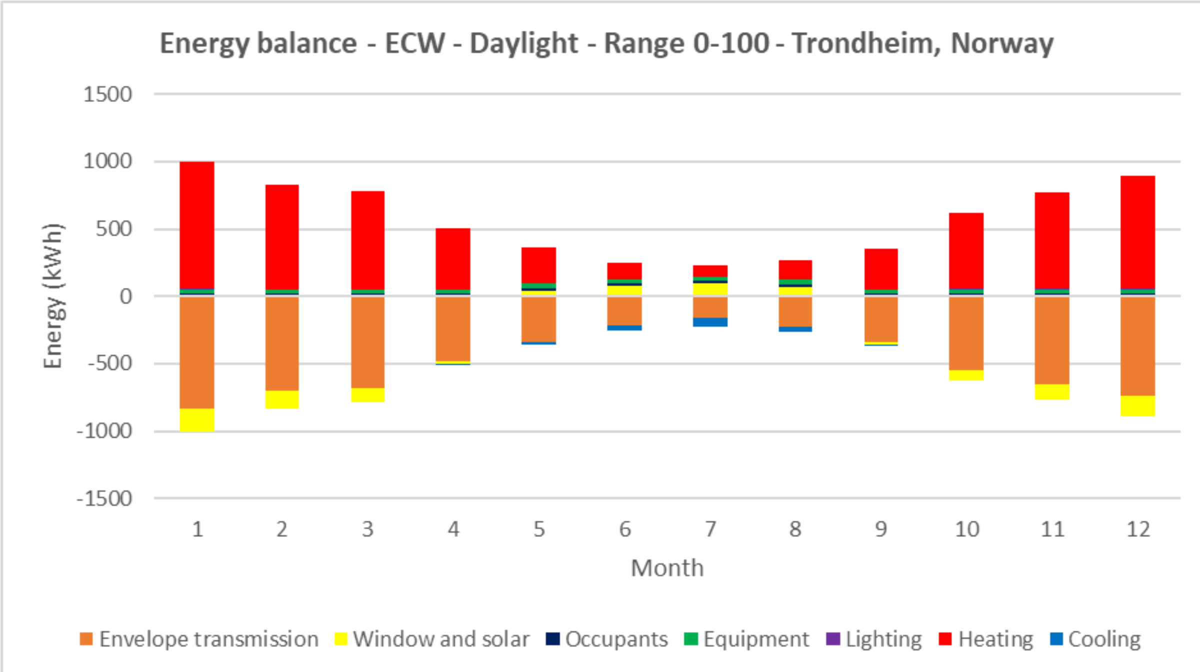

Fig.56. Energy balance - ECW - Daylight - Range 0-100 - Trondheim, Norway. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 28. Energy balance - ECW - Daylight - Range 0-100 - Trondheim, Norway. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - ECW - Daylight - Range 0-100 - Trondheim, Norway (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-833	-170	19	35	6	944	0
2	-703	-128	17	30	2	783	0
3	-679	-105	18	33	0	732	0
4	-485	-20	18	32	0	456	-1
5	-341	44	20	35	0	262	-18
6	-218	79	17	32	0	125	-35
7	-163	96	17	33	0	80	-64
8	-224	68	18	35	0	147	-44
9	-345	-10	17	30	1	310	-3
10	-551	-72	19	35	2	568	0
11	-653	-114	18	33	4	711	0
12	-738	-153	18	32	7	835	0
Total	**-5932**	**-486**	**216**	**392**	**22**	**5952**	**-165**
During heating (7255.6 h)	-5628	-792	158	286	22	5953	0
During cooling (942.3 h)	-169	226	38	71	0	0	-165
Rest of time	-135	80	19	35	0	-1	0

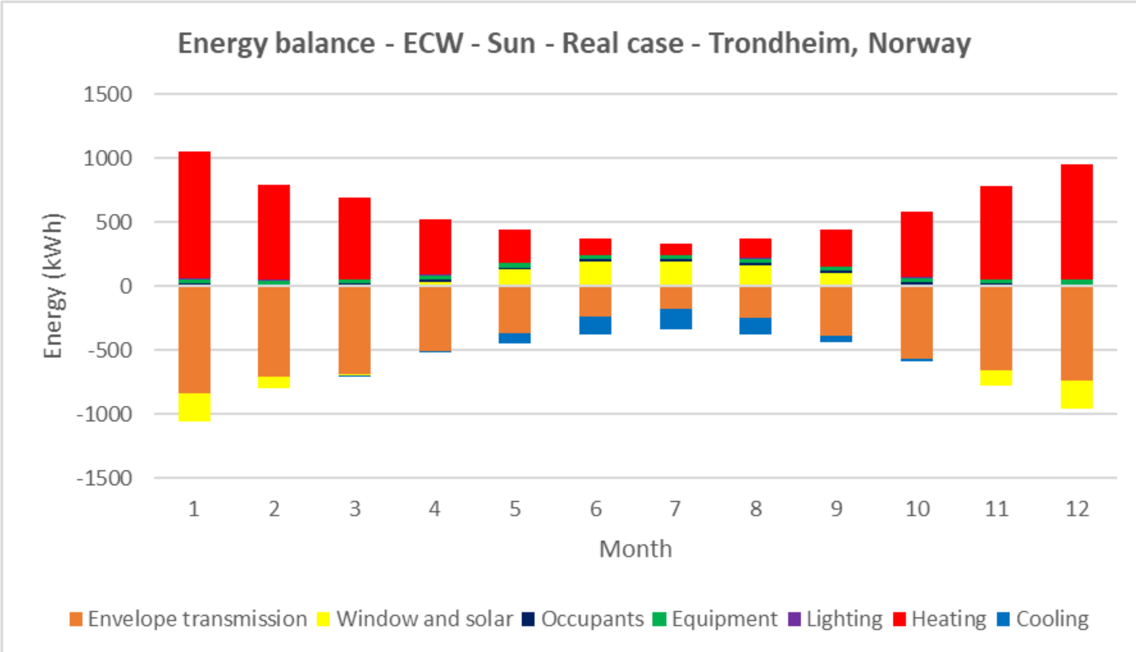

Fig.57. Energy balance - ECW - Sun - Real case - Trondheim, Norway. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 29. Energy balance - ECW - Sun - Real case - Trondheim, Norway. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - ECW - Sun - Real case - Trondheim, Norway (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-832	-222	19	35	7	993	0
2	-703	-92	17	30	4	745	0
3	-691	-2	19	33	4	638	-1
4	-504	38	17	32	5	430	-16
5	-363	129	18	35	4	261	-82
6	-240	192	16	32	2	133	-134
7	-176	194	17	33	3	91	-162
8	-244	165	18	35	4	153	-131
9	-382	108	16	30	4	284	-59
10	-571	13	19	35	4	513	-11
11	-653	-125	18	33	6	721	0
12	-736	-218	18	32	8	896	0
Total	**-6096**	**180**	**212**	**392**	**54**	**5856**	**-595**
During heating (6475.6 h)	-5128	-1103	119	216	35	5856	0
During cooling (1672 h)	-649	1025	72	136	17	0	-595
Rest of time	-319	259	21	39	2	1	0

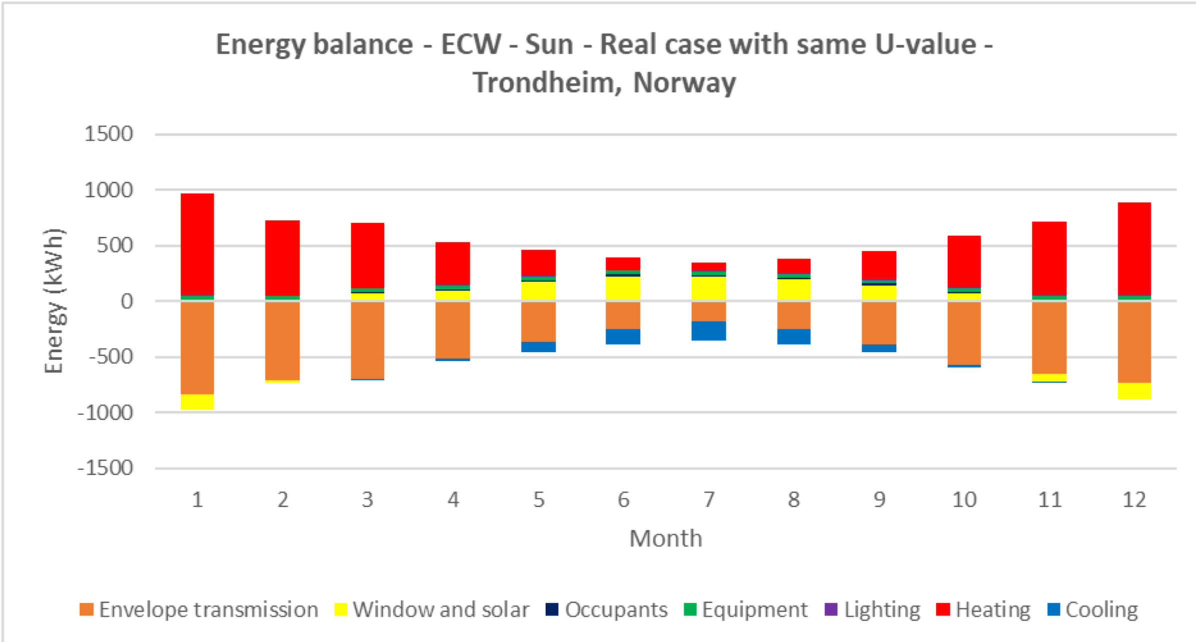

Fig.58. Energy balance - ECW - Sun - Real case with same U-value - Trondheim, Norway. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 30. Energy balance - ECW - Sun - Real case with same U-value - Trondheim, Norway. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - ECW - Sun - Real case with same U-value - Trondheim, Norway (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-833	-141	19	35	7	913	0
2	-705	-22	17	30	4	678	0
3	-696	68	19	33	4	576	-2
4	-510	94	17	32	5	384	-21
5	-368	171	18	35	4	230	-90
6	-245	227	16	32	2	114	-146
7	-181	222	17	33	3	78	-172
8	-246	195	18	35	4	135	-140
9	-385	145	16	30	4	256	-66
10	-575	69	19	35	4	464	-15
11	-655	-61	18	33	6	659	0
12	-737	-146	18	32	8	825	0
Total	**-6136**	**820**	**212**	**392**	**54**	**5311**	**-651**
During heating (6328.2 h)	-5047	-624	114	207	34	5311	0
During cooling (1807.4 h)	-751	1168	77	146	18	0	-651
Rest of time	-338	276	21	38	2	0	0

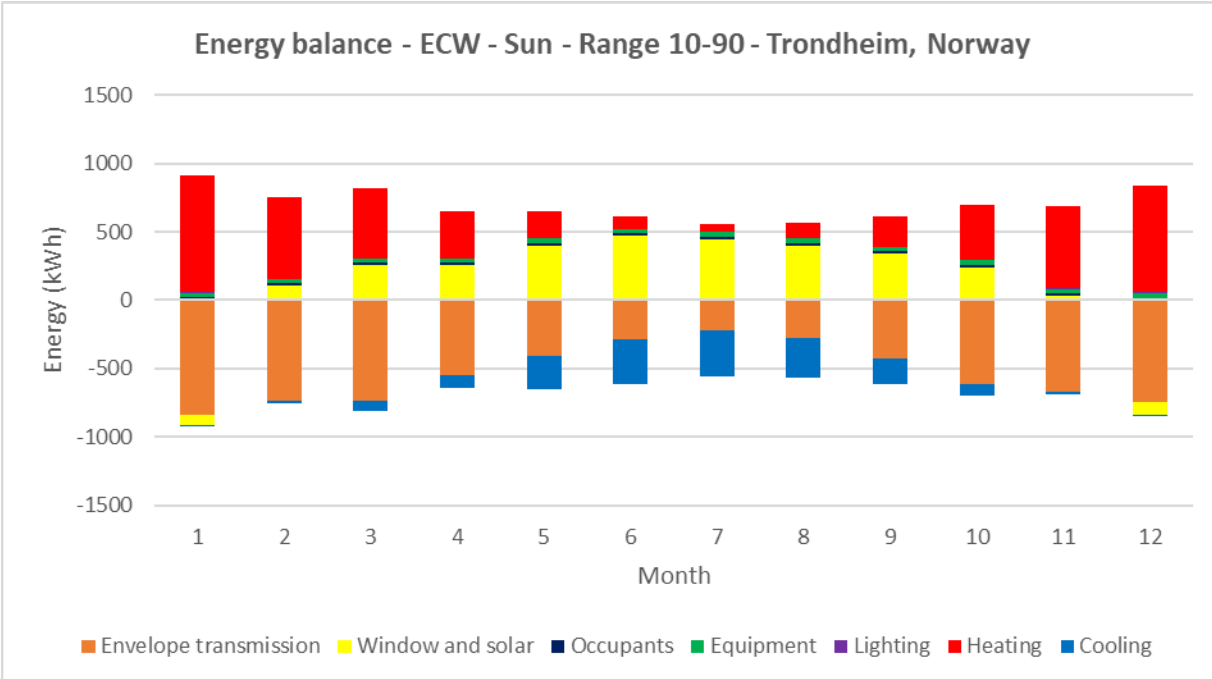

Fig.59. Energy balance - ECW - Sun - Range 10-90 - Trondheim, Norway. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 31. Energy balance - ECW - Sun - Range 10-90 - Trondheim, Norway. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - ECW - Sun - Range 10-90 - Trondheim, Norway (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-840	-70	19	35	6	851	-1
2	-732	105	16	30	2	598	-19
3	-740	256	18	33	1	508	-75
4	-549	256	16	32	0	341	-96
5	-409	400	18	35	0	195	-239
6	-289	475	16	32	0	88	-323
7	-220	446	17	33	0	60	-336
8	-281	400	18	35	0	116	-288
9	-423	343	16	30	1	227	-193
10	-613	240	18	35	2	403	-84
11	-672	29	18	33	4	603	-15
12	-742	-98	18	32	7	784	0
Total	**-6510**	**2782**	**208**	**392**	**22**	**4775**	**-1670**
During heating (5627.4 h)	-4567	-481	85	157	21	4775	0
During cooling (2522.8 h)	-1538	2919	102	196	0	0	-1669
Rest of time	-406	344	21	39	1	0	0

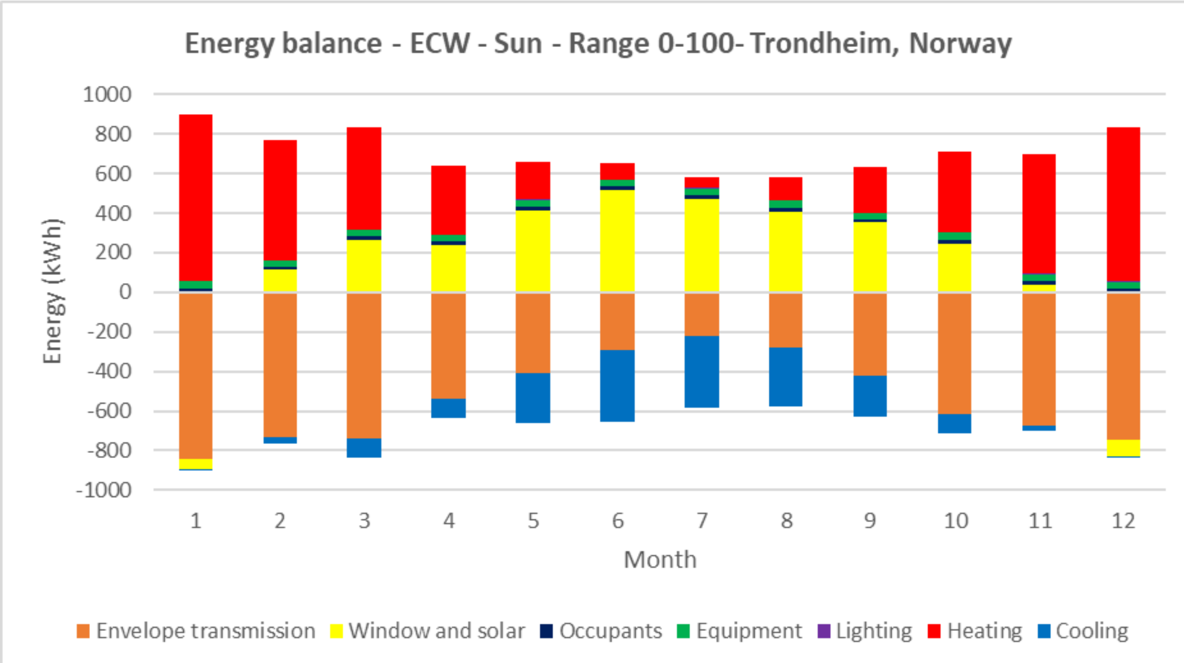

Fig.60. Energy balance - ECW - Sun - Range 0-100 - Trondheim, Norway. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 32. Energy balance - ECW - Sun - Range 0-100 - Trondheim, Norway. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - ECW - Sun - Range 0-100 - Trondheim, Norway (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-842	-55	19	35	6	839	-2
2	-735	113	16	30	3	603	-30
3	-739	263	18	33	3	517	-94
4	-540	240	17	32	4	346	-97
5	-410	414	18	35	4	191	-251
6	-294	518	16	32	2	84	-358
7	-223	474	17	33	2	57	-361
8	-281	409	18	35	3	113	-297
9	-423	354	16	30	3	228	-208
10	-614	248	18	35	4	410	-99
11	-674	41	18	33	5	601	-23
12	-744	-86	18	32	7	775	-1
Total	**-6520**	**2932**	**208**	**392**	**45**	**4763**	**-1820**
During heating (5616.8 h)	-4514	-526	85	157	25	4764	0
During cooling (2554.4 h)	-1626	3139	103	198	17	0	-1820
Rest of time	-380	319	20	38	3	-1	0

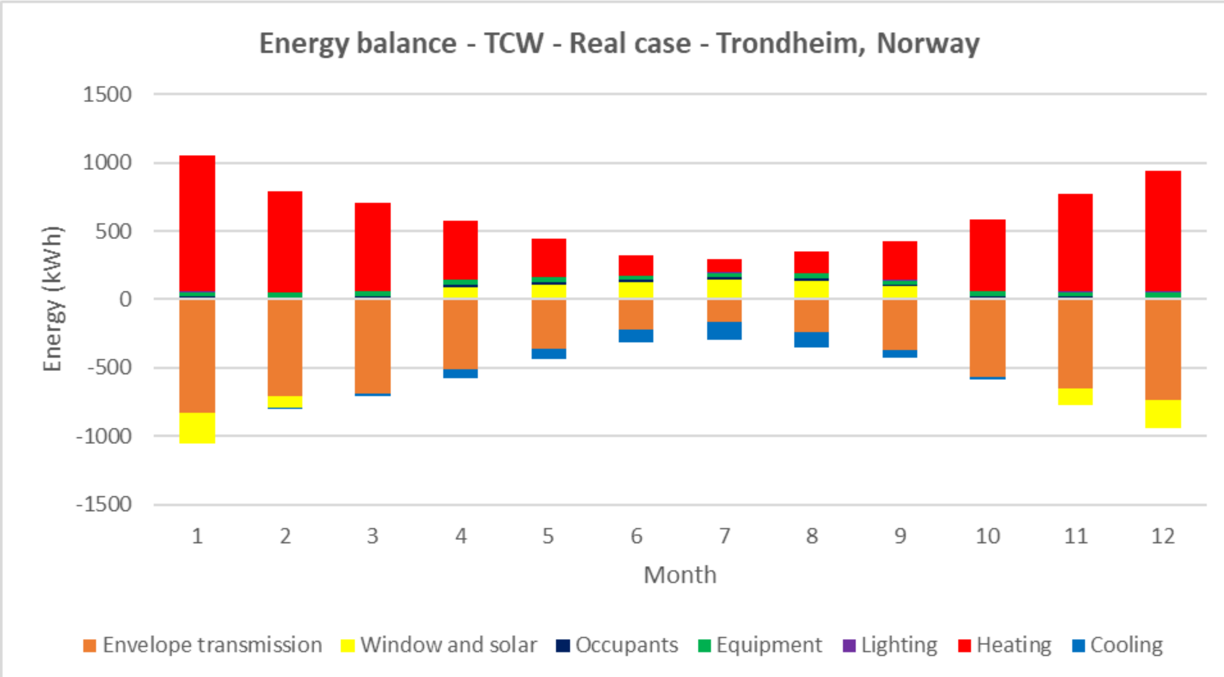

Fig.61. Energy balance - TCW - Real case - Trondheim, Norway. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 33. Energy balance - TCW - Real case - Trondheim, Norway. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - TCW - Real case - Trondheim, Norway (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-832	-221	19	35	7	991	0
2	-704	-87	17	30	3	742	0
3	-694	7	18	33	1	651	-16
4	-514	92	17	32	1	434	-61
5	-357	111	18	35	0	277	-84
6	-225	124	17	32	0	146	-93
7	-164	146	17	33	0	101	-133
8	-235	136	18	35	1	160	-114
9	-373	93	16	30	1	289	-56
10	-567	7	19	35	2	520	-16
11	-651	-125	18	33	6	719	0
12	-736	-208	18	32	8	887	0
Total	**-6052**	**75**	**212**	**392**	**31**	**5917**	**-573**
During heating (6809.3 h)	-5286	-1038	132	240	31	5917	0
During cooling (1428.3 h)	-548	945	62	118	0	0	-573
Rest of time	-218	168	18	33	0	1	0

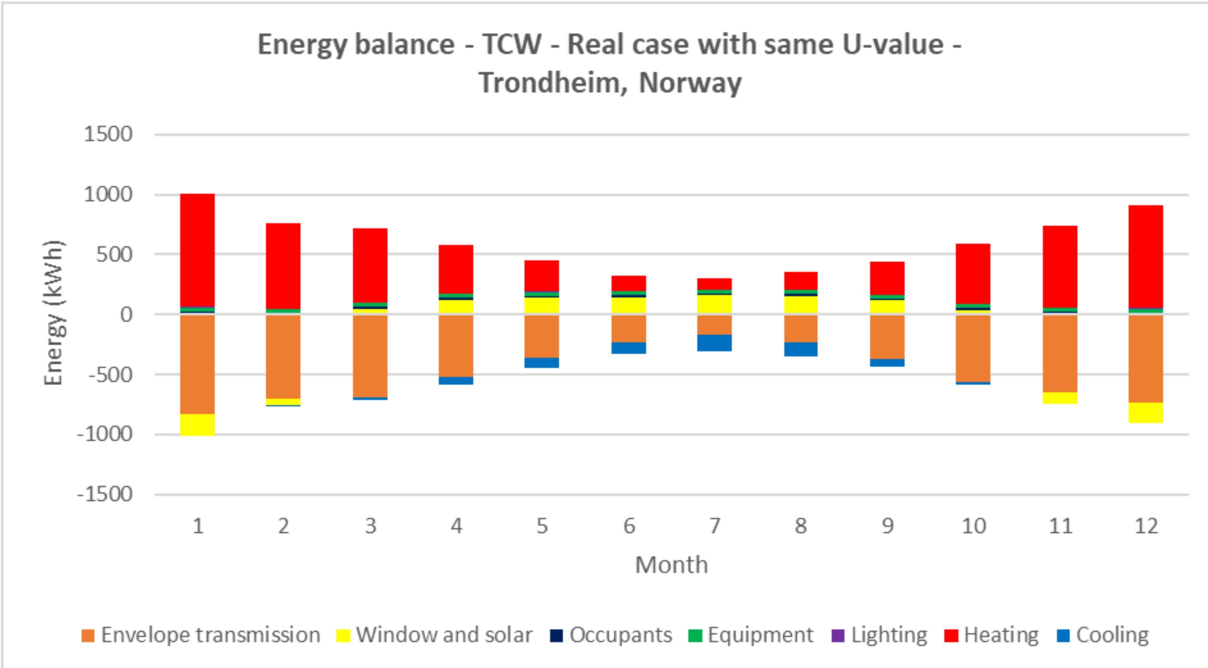

Fig.62. Energy balance - TCW - Real case with same U-value - Trondheim, Norway. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 34. Energy balance - TCW - Real case with same U-value - Trondheim, Norway.Each category is presented per month and during heating, cooling and rest of time.

Energy balance - TCW - Real case with same U-value - Trondheim, Norway (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-832	-177	19	35	7	948	0
2	-705	-50	17	30	3	706	-1
3	-695	45	18	33	1	616	-18
4	-517	123	17	32	1	411	-65
5	-359	136	18	35	0	259	-88
6	-228	142	17	32	0	135	-97
7	-168	160	17	33	0	93	-137
8	-237	152	18	35	1	149	-118
9	-376	115	16	30	1	273	-59
10	-569	37	19	35	2	494	-17
11	-652	-90	18	33	6	686	0
12	-737	-170	18	32	8	849	0
Total	**-6073**	**422**	**211**	**392**	**31**	**5618**	**-599**
During heating (6731.6 h)	-5256	-763	129	236	31	5617	0
During cooling (1486.1 h)	-583	1000	64	122	0	0	-599
Rest of time	-234	184	18	34	0	1	0

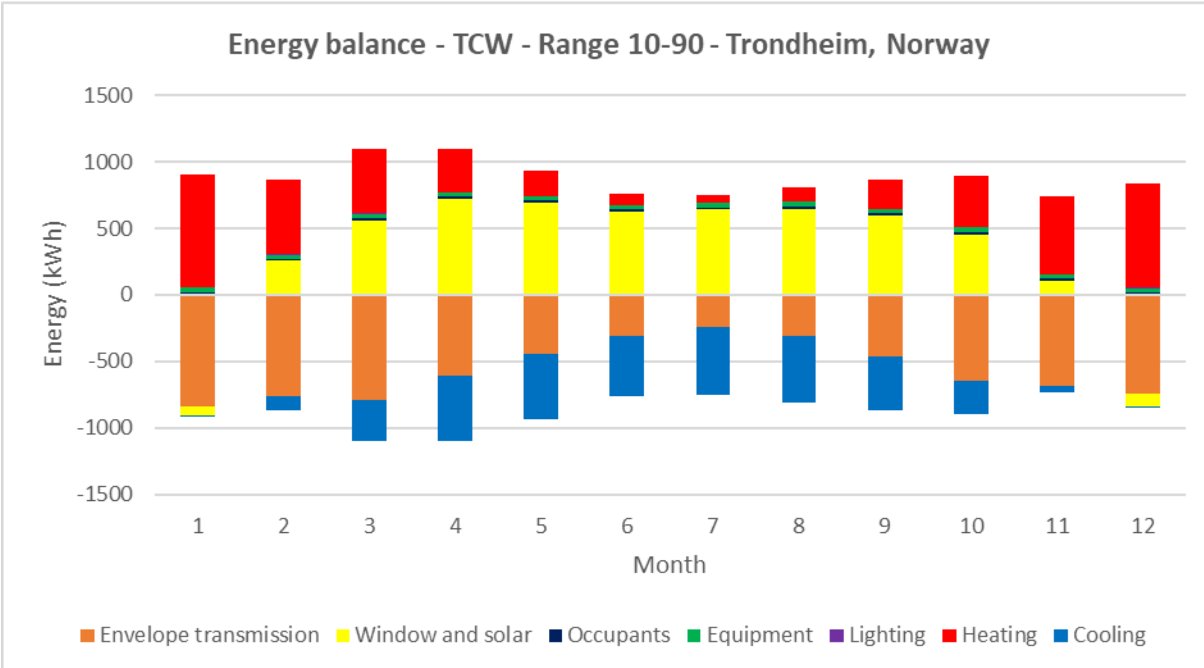

Fig.63. Energy balance - TCW - Range 10-90 - Trondheim, Norway. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 35. Energy balance - TCW - Range 10-90 - Trondheim, Norway. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - TCW - Range 10-90 - Trondheim, Norway (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-841	-65	19	35	6	850	-4
2	-760	256	16	30	2	565	-108
3	-792	561	17	33	0	483	-303
4	-610	725	16	32	0	327	-490
5	-447	692	18	35	0	191	-488
6	-310	627	16	32	0	87	-453
7	-245	642	17	33	0	58	-507
8	-311	649	18	35	0	112	-503
9	-459	599	16	30	1	219	-406
10	-649	454	18	35	2	389	-248
11	-685	102	18	33	4	579	-52
12	-742	-98	18	32	7	784	0
Total	**-6849**	**5145**	**207**	**392**	**22**	**4643**	**-3562**
During heating (5457.7 h)	-4419	-486	81	150	21	4642	0
During cooling (2752.2 h)	-2075	5328	109	210	1	0	-3561
Rest of time	-354	303	17	32	1	1	0

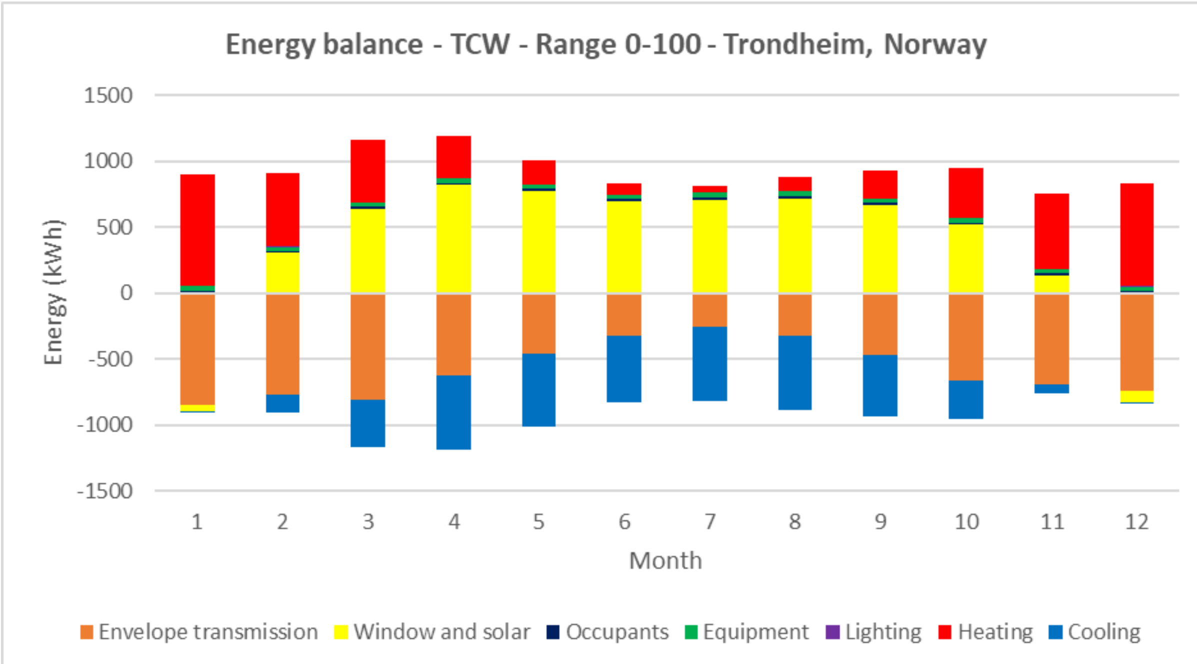

Fig.64. Energy balance - TCW - Range 0-100 - Trondheim, Norway. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 36. Energy balance - TCW - Range 0-100 - Trondheim, Norway. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - TCW - Range 0-100 - Trondheim, Norway (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-844	-47	19	35	6	837	-6
2	-769	304	16	30	2	554	-137
3	-803	640	17	33	0	475	-363
4	-620	820	16	32	0	320	-568
5	-456	774	18	35	0	185	-556
6	-318	699	16	32	0	83	-512
7	-253	710	17	33	0	55	-564
8	-319	719	18	35	0	109	-562
9	-468	671	15	30	1	215	-465
10	-658	518	18	35	2	382	-296
11	-690	132	18	33	4	570	-66
12	-744	-86	18	32	7	775	-1
Total	**-6941**	**5854**	**206**	**392**	**22**	**4559**	**-4094**
During heating (5347.4 h)	-4331	-479	76	142	20	4558	0
During cooling (2865.2 h)	-2255	6028	113	218	1	0	-4094
Rest of time	-355	305	17	32	1	1	0

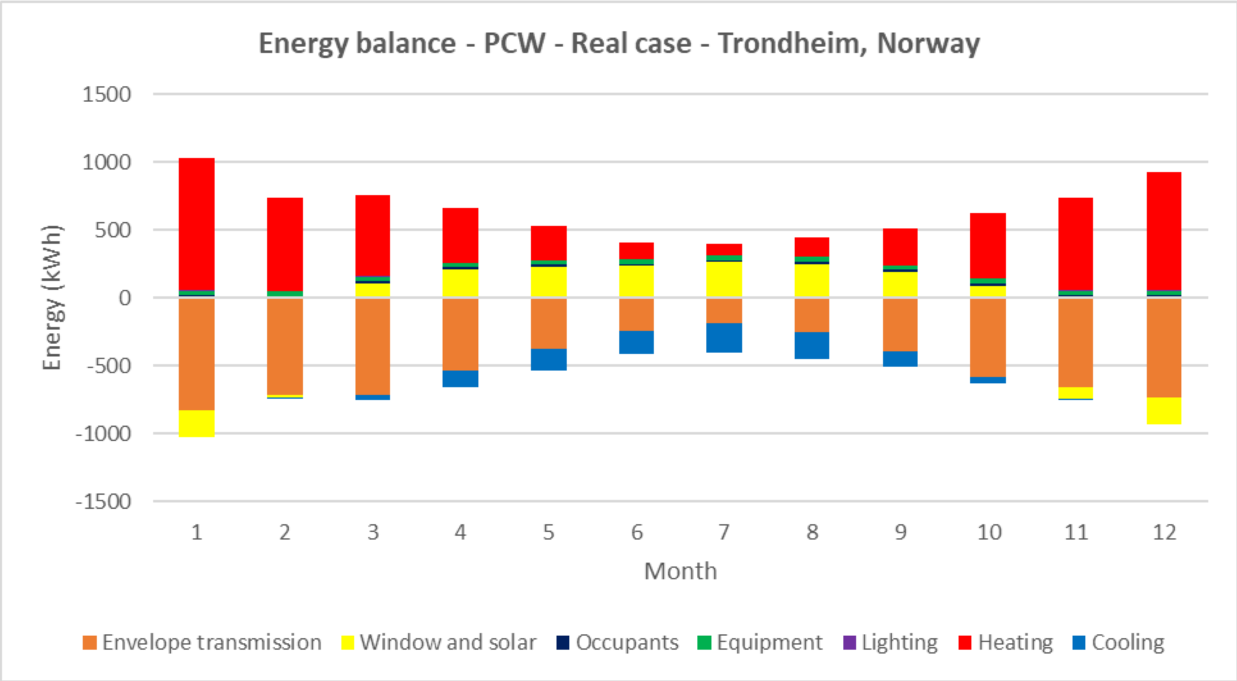

Fig.65. Energy balance - PCW - Real case - Trondheim, Norway. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 37. Energy balance - PCW - Real case - Trondheim, Norway. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - PCW - Real case - Trondheim, Norway (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-832	-195	19	35	7	966	0
2	-710	-25	17	30	2	693	-7
3	-710	107	18	33	1	599	-47
4	-531	210	17	32	1	404	-131
5	-374	227	18	35	0	250	-157
6	-243	234	16	32	0	128	-168
7	-182	263	17	33	0	88	-220
8	-251	251	18	35	1	146	-199
9	-391	194	16	30	1	269	-119
10	-581	89	19	35	2	482	-45
11	-655	-85	18	33	5	685	-1
12	-736	-191	18	32	8	870	0
Total	**-6194**	**1080**	**210**	**392**	**27**	**5578**	**-1091**
During heating (6328.8 h)	-4967	-965	113	207	27	5578	0
During cooling (1849.9 h)	-937	1808	79	150	0	0	-1091
Rest of time	-290	237	19	35	0	0	0

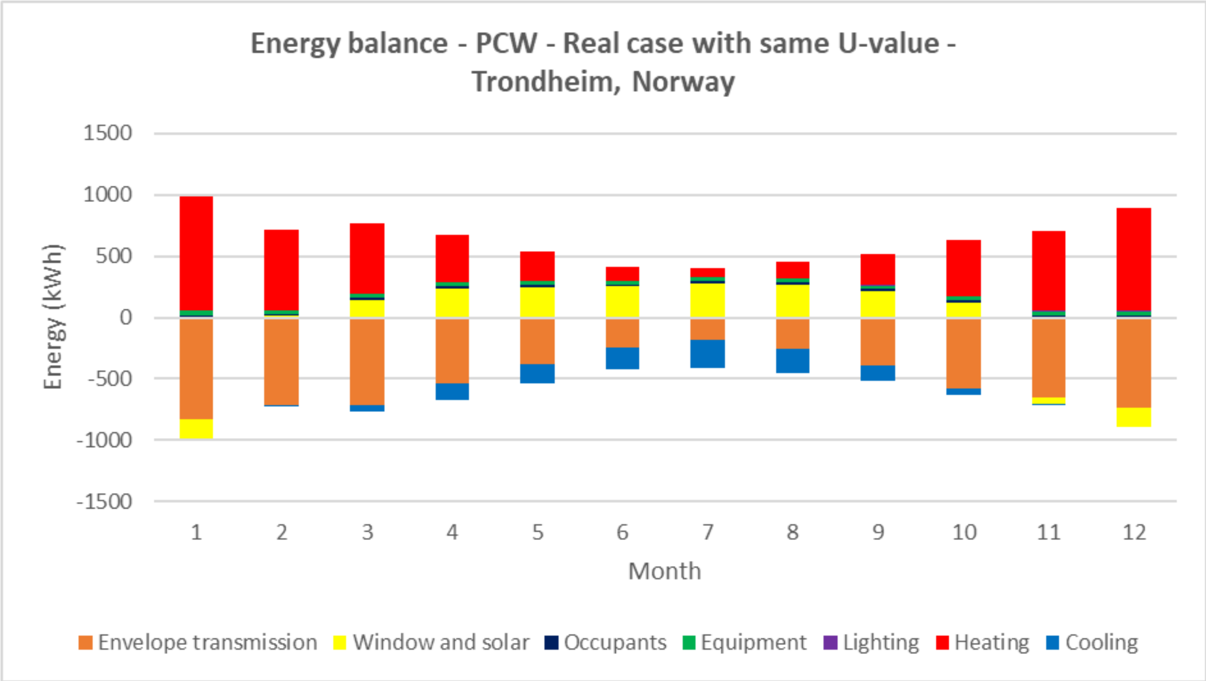

Fig.66. Energy balance - PCW - Real case with same U-value - Trondheim, Norway. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 38. Energy balance - PCW - Real case with same U-value - Trondheim, Norway. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - PCW - Real case with same U-value - Trondheim, Norway (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-832	-152	19	35	7	924	0
2	-712	11	17	30	2	659	-8
3	-712	143	18	33	1	568	-49
4	-534	239	17	32	1	381	-135
5	-377	249	18	35	0	235	-160
6	-245	251	16	32	0	118	-172
7	-184	275	17	33	0	80	-223
8	-254	266	18	35	1	137	-202
9	-393	215	16	30	1	255	-123
10	-583	119	19	35	2	457	-47
11	-656	-51	18	33	5	652	-1
12	-736	-153	18	32	8	833	0
Total	**-6219**	**1412**	**210**	**392**	**27**	**5299**	**-1120**
During heating (6266.9 h)	-4942	-705	111	203	27	5297	0
During cooling (1907.6 h)	-984	1877	81	154	0	0	-1120
Rest of time	-293	241	19	35	0	1	0

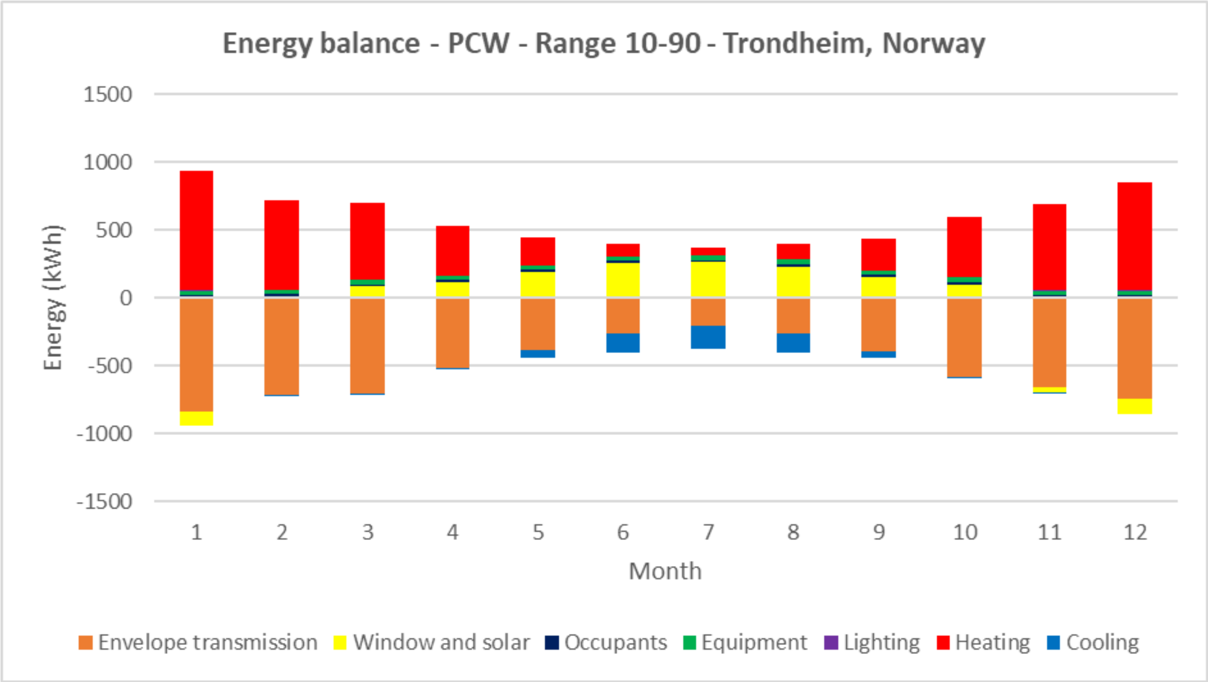

Fig.67. Energy balance - PCW - Range 10-90 - Trondheim, Norway. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 39. Energy balance - PCW - Range 10-90 - Trondheim, Norway. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - PCW - Range 10-90 - Trondheim, Norway (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-837	-102	19	35	6	880	0
2	-715	14	17	30	2	653	0
3	-700	83	19	33	1	567	-1
4	-515	114	18	32	0	364	-12
5	-382	190	18	35	0	201	-62
6	-265	260	16	32	0	91	-134
7	-203	263	17	33	0	61	-172
8	-264	228	18	35	0	119	-136
9	-392	156	16	30	1	239	-48
10	-584	96	19	35	2	442	-8
11	-661	-32	18	33	4	638	0
12	-740	-112	18	32	7	796	0
Total	**-6259**	**1158**	**213**	**392**	**22**	**5049**	**-573**
During heating (6152.3 h)	-5058	-326	109	197	22	5047	0
During cooling (1871.9 h)	-769	1132	75	141	0	0	-573
Rest of time	-431	352	29	53	0	1	0

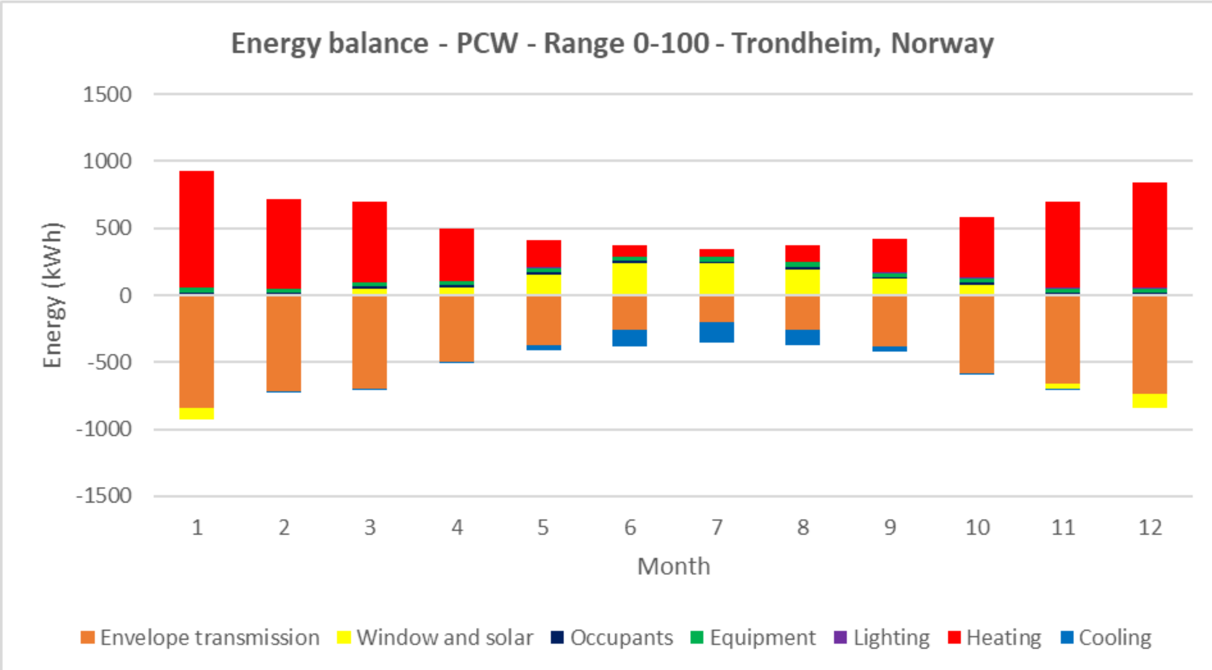

Fig.68. Energy balance - PCW - Range 0-100 - Trondheim, Norway. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 40. Energy balance - PCW - Range 0-100 - Trondheim, Norway. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - PCW - Range 0-100 - Trondheim, Norway (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-837	-95	19	35	6	872	0
2	-714	-1	17	30	3	666	0
3	-693	45	19	33	3	596	-2
4	-494	56	18	32	4	392	-6
5	-371	150	18	35	4	202	-38
6	-262	240	16	32	3	88	-117
7	-198	236	17	33	3	59	-151
8	-257	196	18	35	4	119	-114
9	-380	120	16	30	4	247	-36
10	-579	74	19	35	4	456	-8
11	-661	-36	18	33	5	641	-1
12	-740	-105	18	32	7	789	0
Total	**-6185**	**881**	**213**	**392**	**48**	**5125**	**-473**
During heating (9287.8 h)	-5064	-424	114	208	32	5125	0
During cooling (1703.3 h)	-698	967	68	128	12	0	-473
Rest of time	-424	337	31	56	5	0	0

A.4.5 Energy balance Madrid, Spain

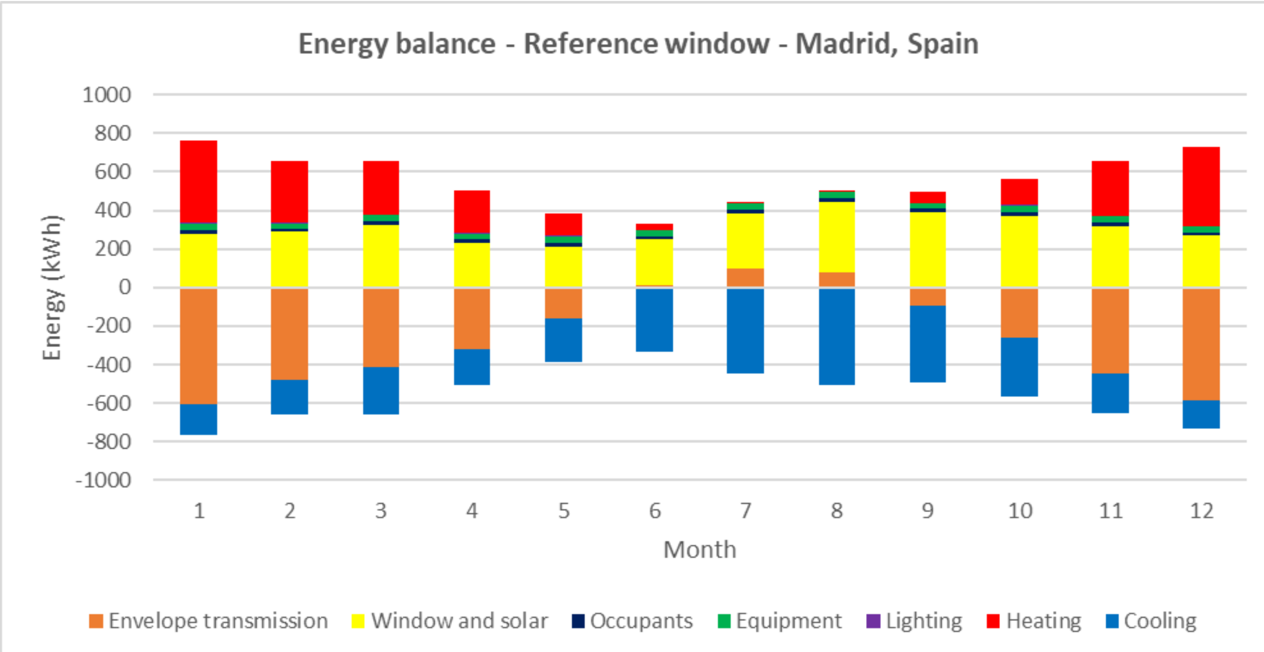

Fig.69. Energy balance - Reference window - Madrid, Spain. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 41. Energy balance - Reference window - Madrid, Spain. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - Reference window - Madrid, spain (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-609	281	18	35	2	428	-153
2	-483	288	16	30	2	324	-176
3	-415	326	17	33	1	281	-244
4	-319	232	16	32	2	223	-185
5	-160	214	18	35	1	117	-225
6	15	233	16	32	1	34	-331
7	98	287	17	33	1	10	-446
8	78	368	18	35	1	5	-506
9	-95	392	16	30	2	55	-400
10	-258	373	18	35	2	138	-307
11	-446	319	17	33	1	285	-209
12	-587	269	17	32	2	413	-144
Total	**-3180**	**3580**	**204**	**392**	**17**	**2313**	**-3325**
During heating (4003.9 h)	-2216	-297	62	119	16	2313	0
During cooling (3898.2 h)	-713	3683	123	236	0	0	-3325
Rest of time	-251	194	19	36	1	0	0

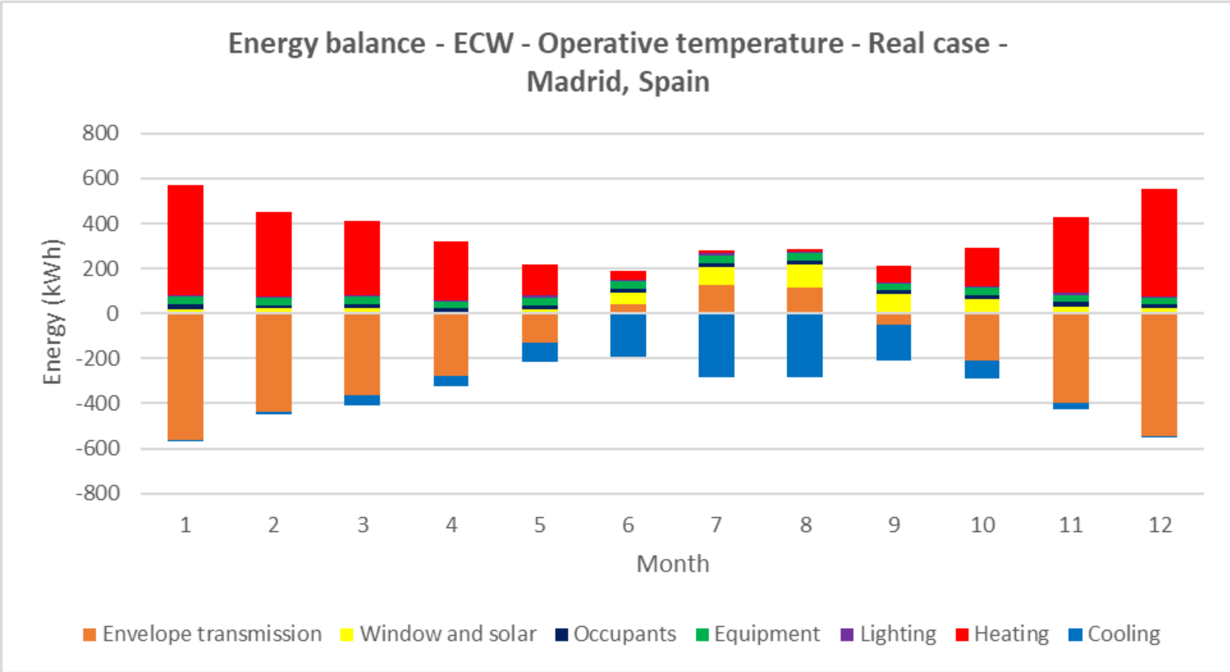

Fig.70. Energy balance - ECW - Operative temperature - Real case - Madrid, Spain. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 42. Energy balance - ECW - Operative temperature - Real case - Madrid, Spain. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - ECW - Operative temperature - Real case - Madrid, spain (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-564	19	19	35	6	491	-6
2	-435	21	16	30	6	378	-15
3	-364	25	17	33	7	328	-46
4	-278	6	17	32	7	261	-43
5	-127	18	18	35	8	139	-90
6	40	54	16	32	8	42	-192
7	125	83	17	33	9	13	-281
8	112	103	18	35	10	8	-286
9	-53	87	16	30	8	69	-157
10	-211	62	18	35	8	169	-81
11	-398	32	18	33	7	336	-28
12	-544	23	17	32	5	474	-7
Total	**-2697**	**533**	**207**	**392**	**89**	**2706**	**-1231**
During heating (4191.9 h)	-2309	-593	61	114	20	2706	0
During cooling (3534.4 h)	-73	872	126	239	68	0	-1231
Rest of time	-314	254	20	38	1	0	0

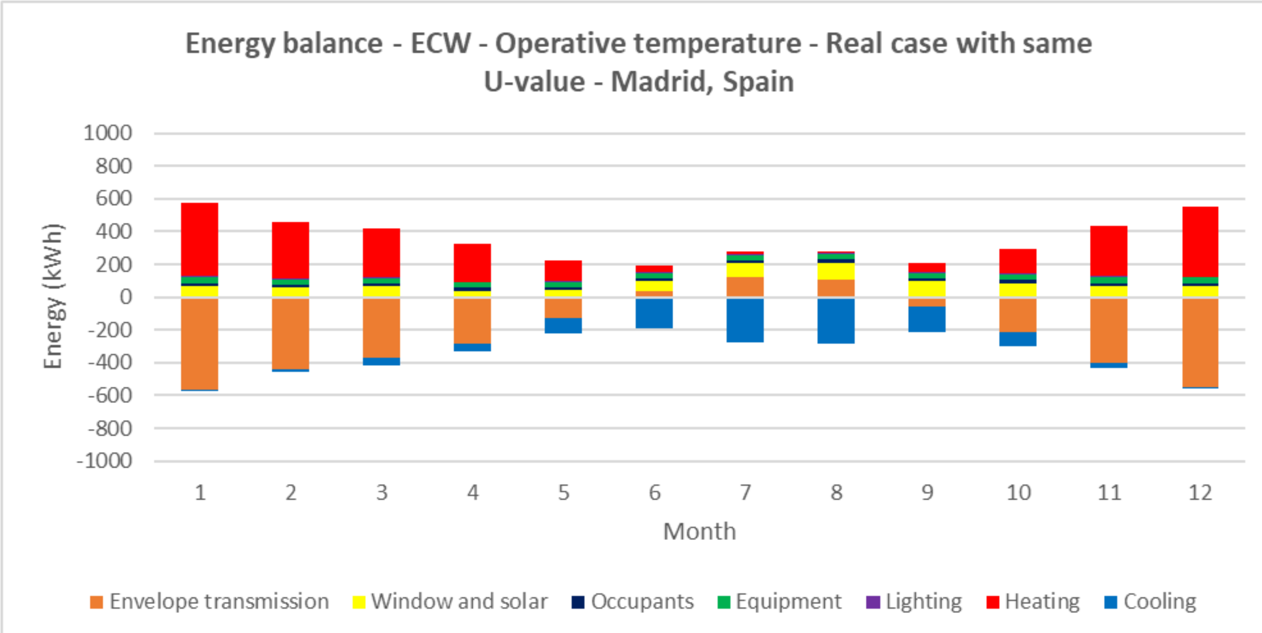

Fig.71. Energy balance - ECW - Operative temp - Real case with same U-value - Madrid, Spain. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 43. Energy balance - ECW - Operative temp - Real case with same U-value - Madrid, Spain. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - ECW - Operative temp - Real case with same U-value - Madrid, spain (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-567	68	19	35	6	448	-8
2	-438	61	16	30	6	344	-18
3	-368	64	17	33	7	297	-50
4	-282	39	17	32	7	235	-46
5	-130	41	18	35	8	123	-93
6	38	62	16	32	8	36	-192
7	124	83	17	33	9	10	-277
8	110	102	18	35	10	6	-281
9	-55	99	16	30	8	60	-158
10	-212	87	18	35	8	150	-85
11	-401	69	18	33	8	305	-31
12	-546	70	17	32	6	431	-9
Total	**-2729**	**843**	**207**	**392**	**90**	**2444**	**-1249**
During heating (4078.2 h)	-2284	-348	58	110	20	2444	0
During cooling (3631.8 h)	-114	921	128	243	69	0	-1249
Rest of time	-331	270	20	39	2	0	0

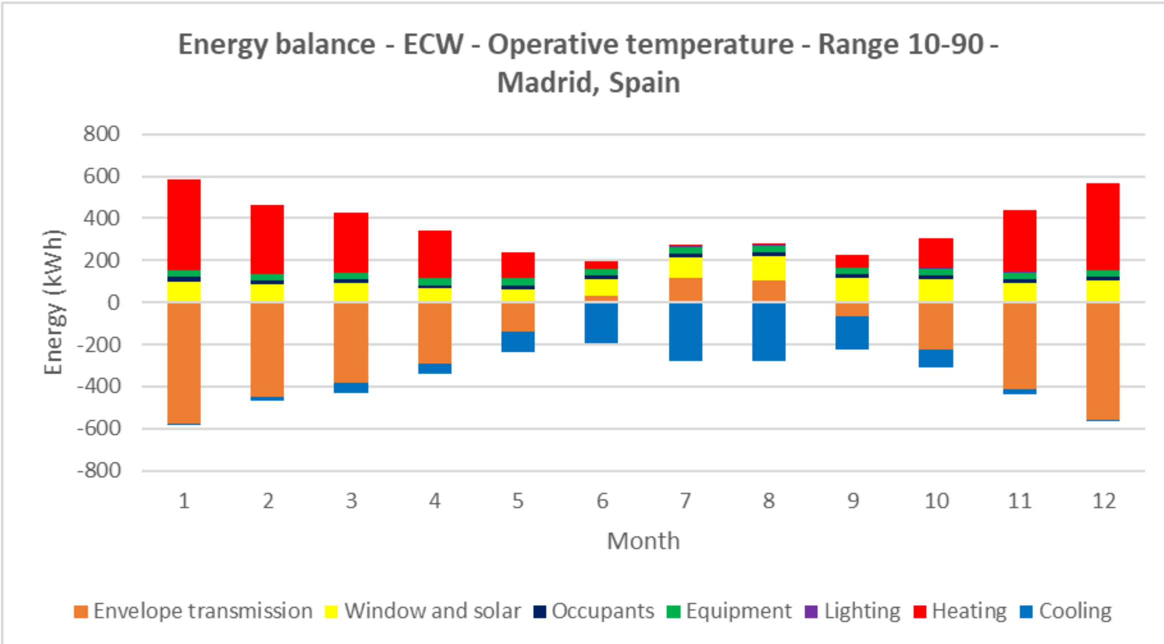

Fig.72. Energy balance - ECW - Operative temperature - Range 10-90 - Madrid, Spain. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 44. Energy balance - ECW - Operative temperature - Range 10-90 - Madrid, Spain. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - ECW - Operative temperature - Range 10-90 - Madrid, Spain (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-579	101	19	35	2	429	-5
2	-450	89	16	30	1	330	-16
3	-380	92	17	33	1	285	-49
4	-292	66	17	32	1	224	-47
5	-139	64	18	35	2	118	-97
6	31	80	16	32	2	34	-196
7	118	96	17	33	3	10	-278
8	104	115	18	35	2	5	-280
9	-64	118	16	30	2	58	-160
10	-224	109	18	35	2	145	-84
11	-412	92	18	33	2	295	-28
12	-559	102	17	32	2	413	-6
Total	**-2847**	**1124**	**207**	**392**	**22**	**2345**	**-1247**
During heating (3855 h)	-2234	-270	49	93	14	2345	0
During cooling (3857.7 h)	-197	1028	141	266	7	0	-1247
Rest of time	-415	365	17	33	1	0	0

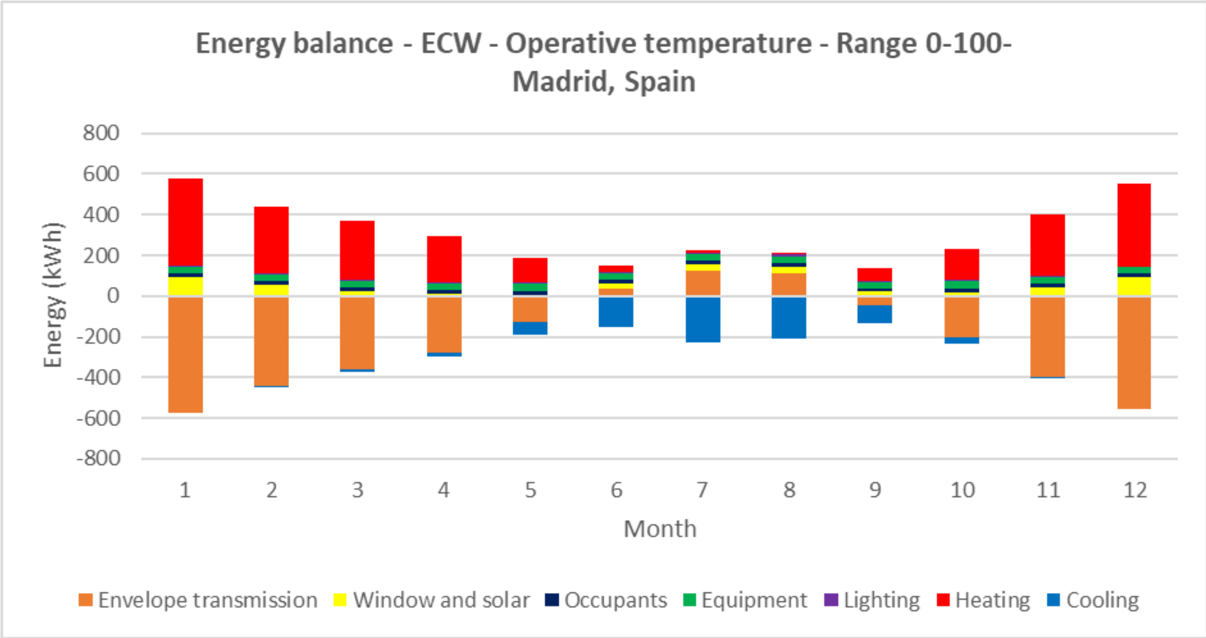

Fig.73. Energy balance - ECW - Operative temperature - Range 0-100 - Madrid, Spain. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 45. Energy balance - ECW - Operative temperature - Range 0-100 - Madrid, Spain. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - ECW - Operative temperature - Range 0-100 - Madrid, Spain (kWh)							
Month	**Envelope transmission**	**Window and solar**	**Occupants**	**Equipment**	**Lighting**	**Heating**	**Cooling**
1	-576	92	20	35	2	427	0
2	-440	58	17	30	4	331	-1
3	-360	24	19	33	7	289	-12
4	-278	14	17	32	7	226	-17
5	-128	8	18	35	8	119	-61
6	40	23	16	32	8	35	-154
7	127	29	17	33	9	10	-227
8	115	28	18	35	9	6	-212
9	-48	21	16	30	8	60	-88
10	-205	20	18	35	8	151	-27
11	-398	45	19	33	5	300	-3
12	-554	92	18	32	2	411	0
Total	**-2704**	**453**	**213**	**392**	**76**	**2365**	**-800**
During heating (3876.3 h)	-2247	-274	49	90	13	2365	0
During cooling (3593.3 h)	16	302	147	270	62	0	-800
Rest of time	-473	424	17	32	1	0	0

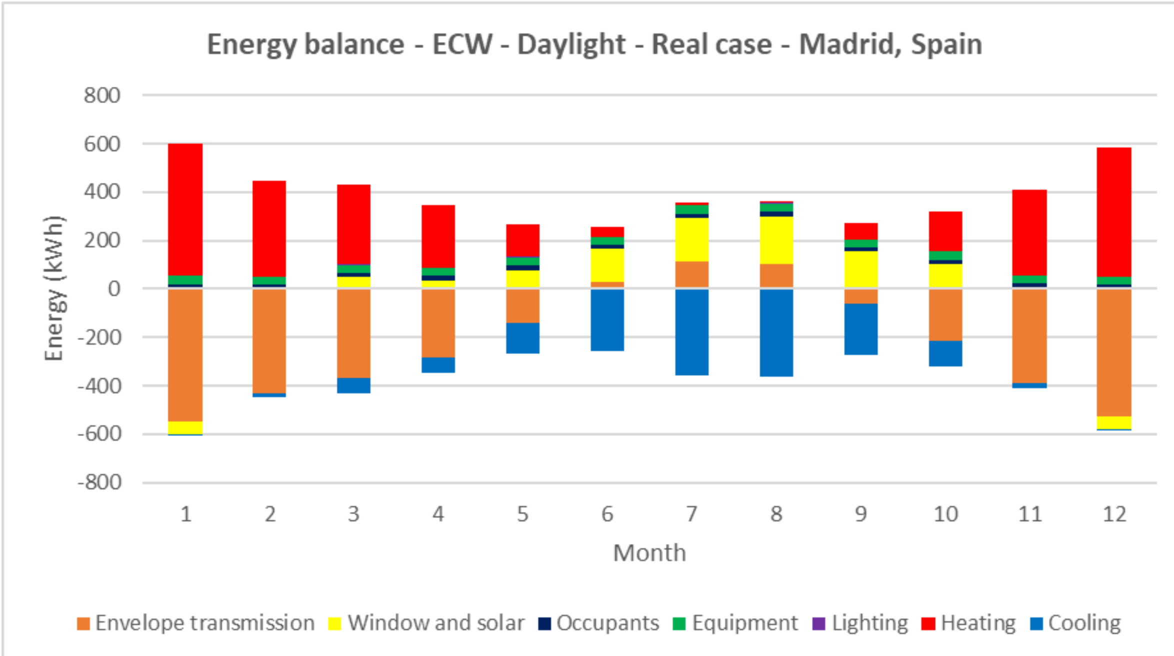

Fig.74. Energy balance - ECW - Daylight - Real case Madrid, Spain. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 46. Energy balance - ECW - Daylight - Real case - Madrid, Spain. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - ECW - Daylight - Real case - Madrid, spain (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-545	-54	19	35	2	544	-1
2	-430	4	16	30	2	394	-16
3	-367	49	17	33	2	328	-63
4	-284	37	17	32	2	258	-61
5	-138	79	18	35	2	134	-129
6	29	135	16	32	1	41	-255
7	114	180	17	33	2	13	-359
8	101	200	18	35	2	7	-363
9	-62	158	16	30	2	67	-211
10	-215	103	18	35	2	163	-107
11	-388	4	18	33	2	352	-21
12	-526	-56	18	32	2	532	-2
Total	**-2710**	**839**	**208**	**392**	**22**	**2833**	**-1588**
During heating (4609.9 h)	-2521	-581	83	156	20	2833	0
During cooling (3126.5 h)	51	1262	97	184	0	0	-1588
Rest of time	-241	158	28	52	1	0	0

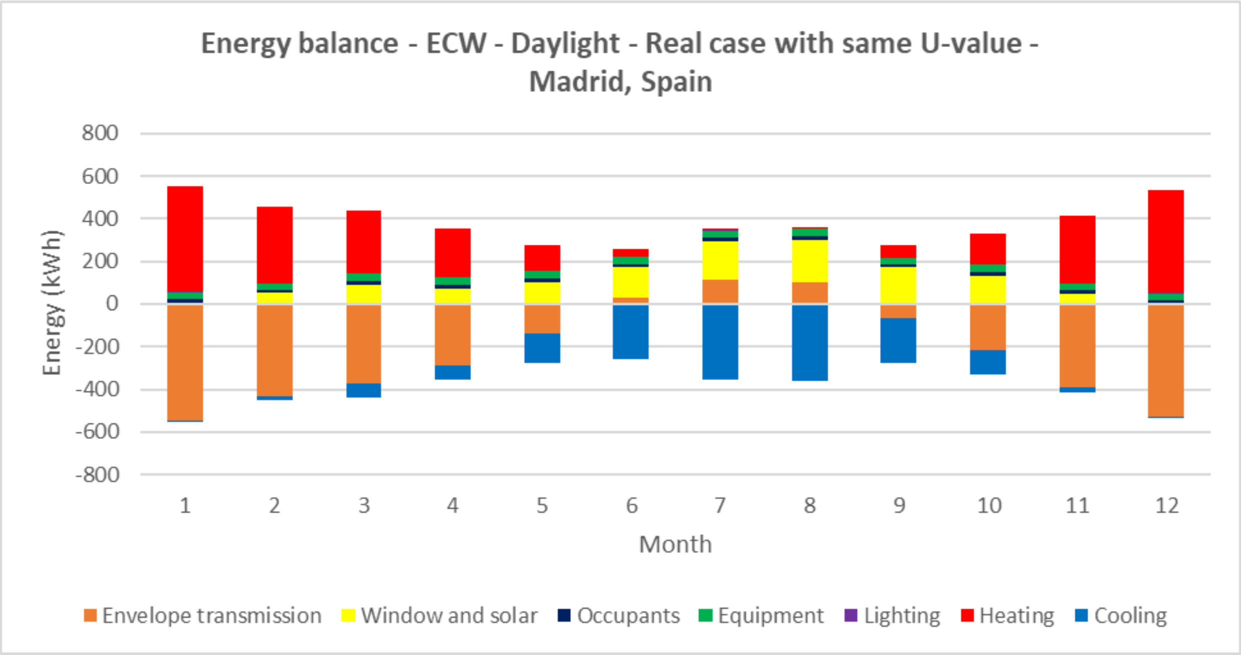

Fig.75. Energy balance - ECW - Daylight - Real case with same U-value - Madrid, Spain. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 47. Energy balance - ECW - Daylight - Real case with same U-value - Madrid, Spain. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - ECW - Daylight - Real case with same U-value - Madrid, spain (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-548	2	19	35	2	492	-1
2	-434	51	16	30	2	355	-20
3	-371	92	17	33	2	295	-69
4	-288	75	17	32	2	230	-67
5	-142	104	18	35	2	118	-135
6	28	145	16	32	1	35	-256
7	113	181	17	33	2	10	-356
8	100	200	18	35	2	5	-360
9	-64	171	16	30	2	58	-213
10	-218	130	18	35	2	144	-112
11	-391	45	18	33	2	317	-24
12	-528	-1	18	32	2	482	-3
Total	**-2745**	**1194**	**208**	**392**	**22**	**2540**	**-1615**
During heating (4469.2 h)	-2489	-311	80	150	20	2540	0
During cooling (3246.2 h)	5	1324	101	191	0	0	-1615
Rest of time	-262	181	27	51	2	0	0

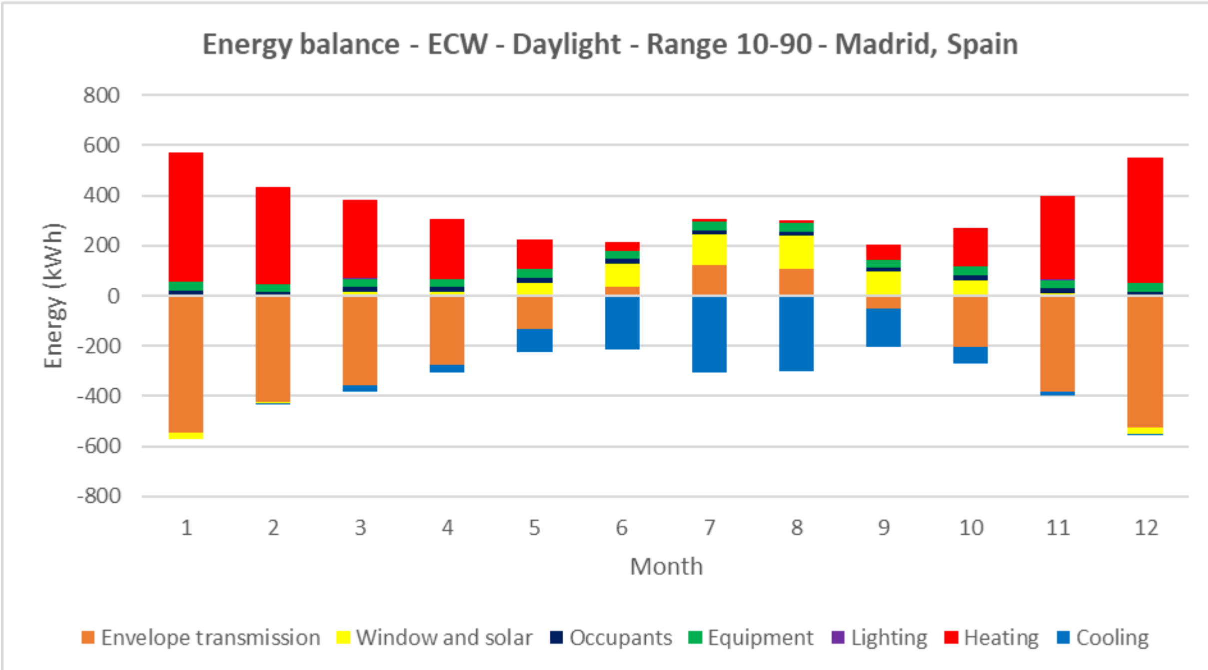

Fig.76. Energy balance - ECW - Daylight - Range 10-90 - Madrid, Spain. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 48. Energy balance - ECW - Daylight - Range 10-90 - Madrid, Spain. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - ECW - Daylight - Range 10-90 - Madrid, Spain (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-543.7	-29.6	19.3	34.5	1.8	517.6	0
2	-421	-6	17	30	1	383	-5
3	-356	18	18	33	1	312	-27
4	-274	17	17	32	1	239	-31
5	-130	53	18	35	1	118	-94
6	35	95	16	32	1	34	-212
7	121	124	17	33	1	10	-306
8	109	130	18	35	1	5	-299
9	-52	97	16	30	2	58	-150
10	-206	63	18	35	2	151	-62
11	-385	12	18	33	1	331	-12
12	-525	-27	18	32	2	502	-1
Total	**-2628**	**547**	**210**	**392**	**15**	**2661**	**-1198**
During heating (4764.8 h)	-2636	-311	93	171	14	2661	0
During cooling (2827.8 h)	271	693	82	155	0	0	-1198
Rest of time	-264	165	35	65	1	0	0

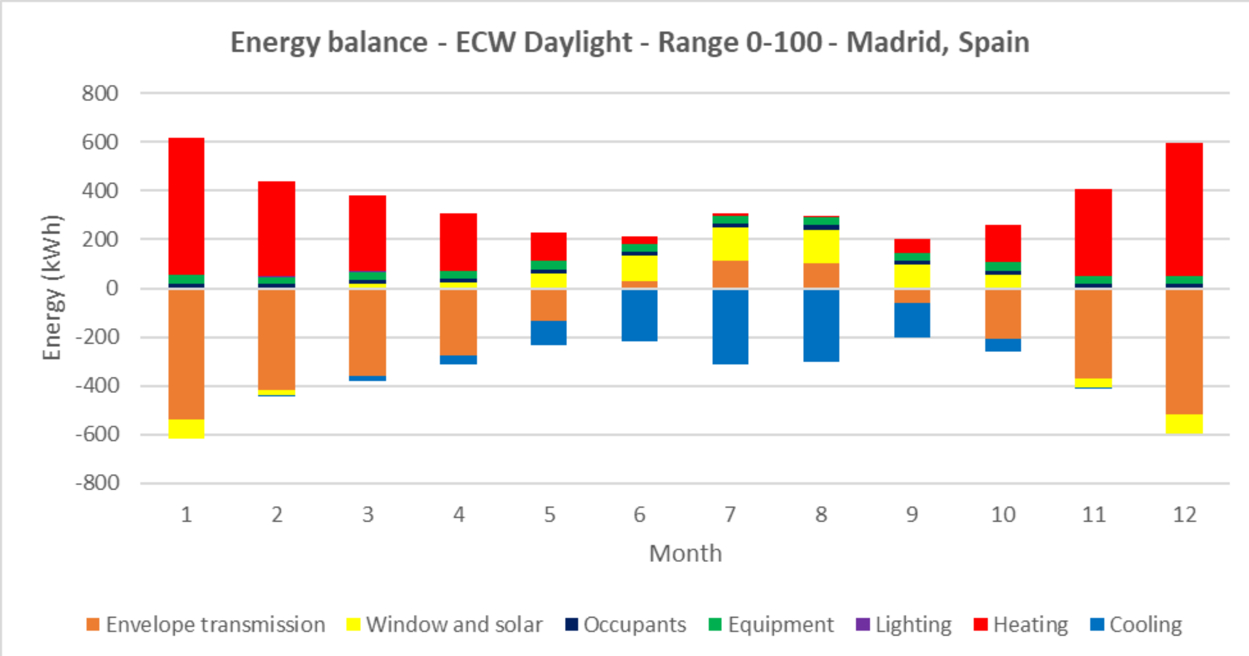

Fig.77. Energy balance - ECW - Daylight - Range 0-100 - Madrid, Spain. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 49. Energy balance - ECW - Daylight - Range 0-100 - Madrid, Spain. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - ECW - Daylight - Range 0-100 - Madrid, Spain (kWh)							
Month	**Envelope transmission**	**Window and solar**	**Occupants**	**Equipment**	**Lighting**	**Heating**	**Cooling**
1	-536	-80	19	35	2	561	0
2	-417	-21	17	30	1	391	-1
3	-357	17	18	33	1	310	-23
4	-278	22	17	32	1	238	-32
5	-136	61	18	35	1	117	-96
6	28	105	16	32	0	34	-216
7	112	136	17	33	1	10	-310
8	100	139	18	35	1	5	-300
9	-58	98	16	30	1	58	-145
10	-207	54	18	35	2	150	-52
11	-372	-33	18	33	1	355	-2
12	-517	-81	18	32	1	547	0
Total	**-2637**	**417**	**210**	**392**	**14**	**2773**	**-1177**
During heating (4999.8 h)	-2729	-364	105	193	13	2773	0
During cooling (2772.7 h)	259	690	80	151	0	0	-1177
Rest of time	-167	91	26	48	1	0	0

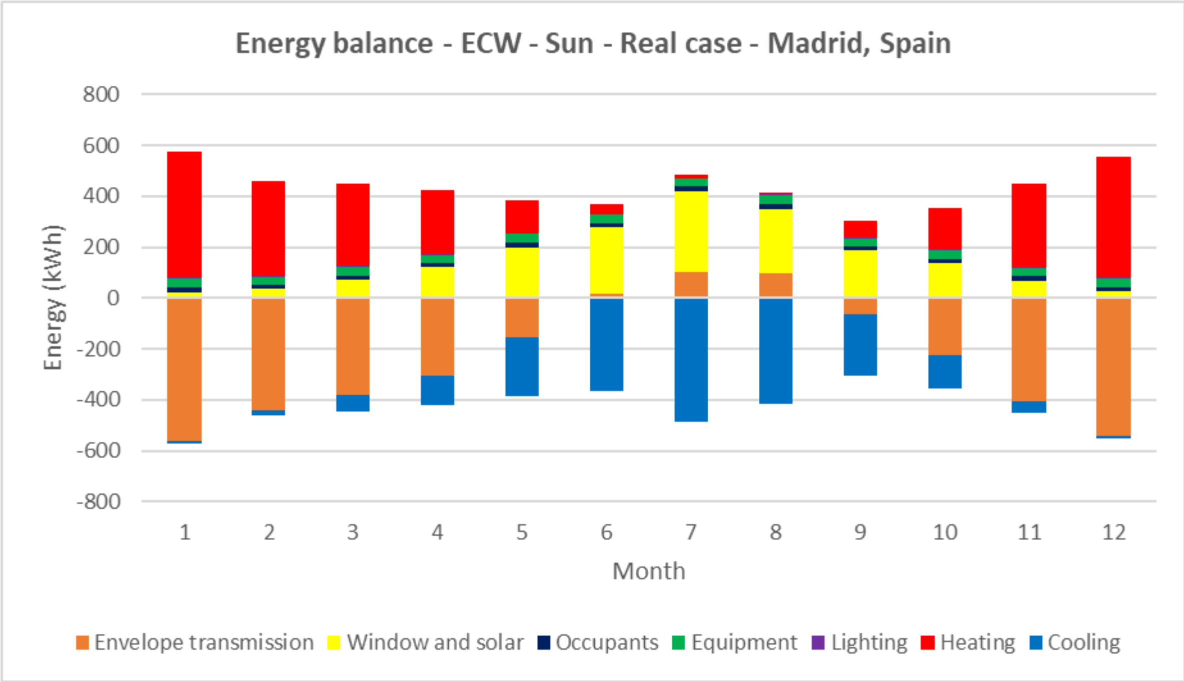

Fig.78. Energy balance - ECW - Sun - Real case - Madrid, Spain. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 50. Energy balance - ECW - Sun - Real case - Madrid, Spain. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - ECW - Sun - Real case - Madrid, spain (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-562	23	19	35	6	491	-10
2	-439	37	16	30	6	372	-20
3	-380	72	17	33	7	318	-67
4	-306	122	16	32	5	248	-116
5	-155	200	18	35	3	131	-231
6	14	264	16	32	1	40	-368
7	100	319	17	33	2	12	-484
8	99	252	18	35	6	7	-417
9	-66	188	16	30	6	66	-240
10	-225	135	18	35	7	159	-129
11	-406	68	17	33	6	326	-43
12	-543	26	17	32	6	473	-10
Total	**-2868**	**1705**	**206**	**392**	**61**	**2642**	**-2134**
During heating (4178.8 h)	-2275	-568	61	116	21	2642	0
During cooling (3596.1 h)	-283	2044	119	228	34	0	-2134
Rest of time	-310	229	26	48	6	0	0

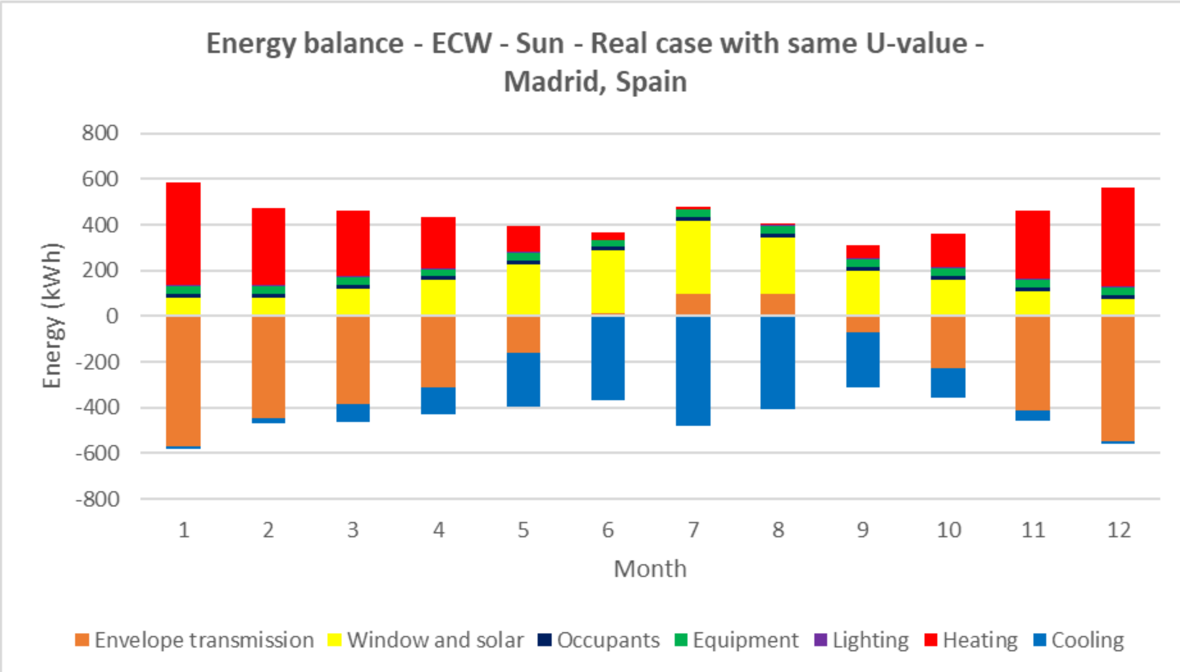

Fig.79. Energy balance - ECW - Sun - Real case with same U-value - Madrid, Spain. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 51. Energy balance - ECW - Sun - Real case with same U-value - Madrid, Spain. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - ECW - Sun - Real case with same U-value - Madrid, spain (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-568	80	19	35	6	444	-15
2	-445	83	16	30	6	335	-25
3	-385	118	17	33	7	287	-77
4	-310	158	16	32	5	222	-122
5	-159	227	18	35	3	115	-237
6	13	274	16	32	1	33	-369
7	98	320	17	33	2	9	-480
8	96	248	18	35	6	5	-408
9	-68	201	16	30	6	57	-242
10	-227	157	18	35	7	142	-132
11	-410	108	17	33	6	295	-49
12	-547	77	17	32	6	429	-13
Total	**-2911**	**2052**	**206**	**392**	**61**	**2374**	**-2170**
During heating (4042.6 h)	-2236	-328	58	110	19	2373	0
During cooling (3715.2 h)	-348	2131	123	235	36	0	-2170
Rest of time	-327	248	25	47	6	0	0

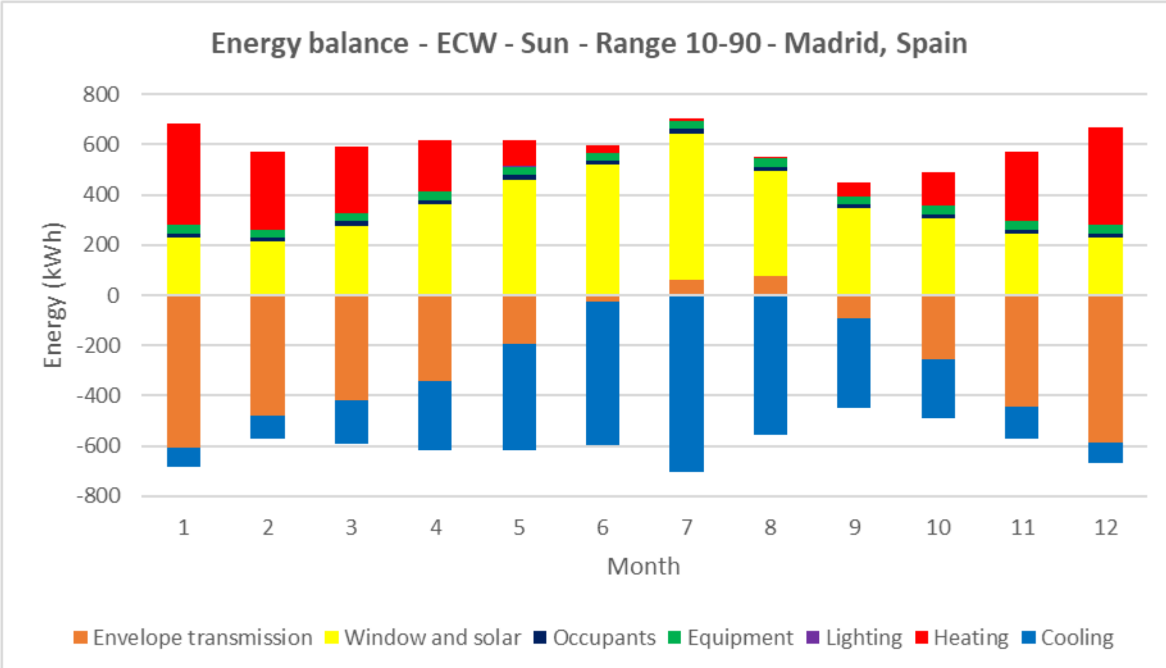

Fig.80. Energy balance - ECW - Sun - Range 10-90 - Madrid, Spain. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 52. Energy balance - ECW - Sun - Range 10-90 - Madrid, Spain. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - ECW - Sun - Range 10-90 - Madrid, Spain (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-605	228	18	35	2	403	-80
2	-480	216	16	30	1	308	-90
3	-417	277	17	33	1	265	-176
4	-341	363	16	32	1	204	-274
5	-196	460	18	35	1	104	-423
6	-24	519	16	32	1	29	-574
7	63	582	17	33	1	8	-705
8	78	417	18	35	1	5	-554
9	-90	347	16	30	1	53	-357
10	-253	304	18	35	2	129	-235
11	-442	245	17	33	1	274	-129
12	-587	231	17	32	2	386	-79
Total	**-3292**	**4188**	**204**	**392**	**15**	**2168**	**-3674**
During heating (3650.3 h)	-2084	-245	48	92	14	2168	0
During cooling (4296.2 h)	-930	4203	141	271	0	0	-3675
Rest of time	-278	230	15	29	1	0	1

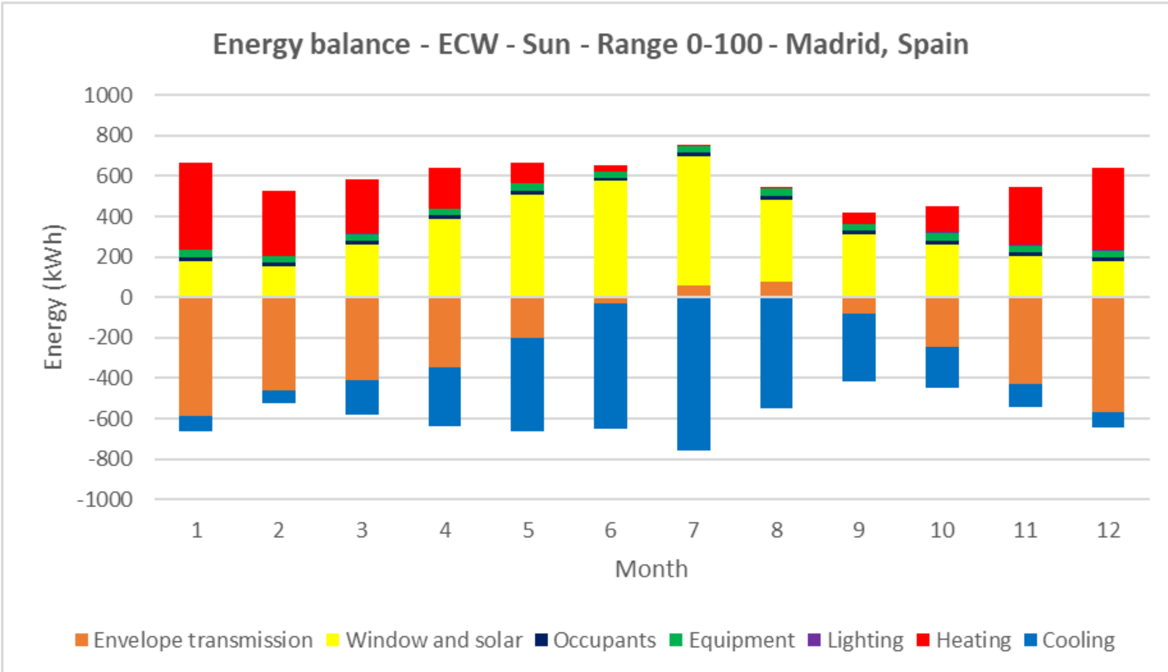

Fig.81. Energy balance - ECW - Sun - Range 0-100 - Madrid, Spain. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 53. Energy balance - ECW - Sun - Range 0-100 - Madrid, Spain. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - ECW - Sun - Range 0-100 - Madrid, Spain (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-586	179	18	35	6	426	-78
2	-459	155	16	30	6	318	-65
3	-412	262	17	33	7	265	-172
4	-345	388	16	32	4	201	-295
5	-202	509	18	35	2	103	-464
6	-31	575	16	32	0	29	-622
7	56	641	17	33	1	8	-757
8	79	406	18	35	5	5	-547
9	-81	314	16	30	5	53	-337
10	-245	262	18	35	7	130	-206
11	-430	206	17	33	6	282	-115
12	-571	181	17	32	6	409	-72
Total	**-3227**	**4078**	**204**	**392**	**54**	**2227**	**-3730**
During heating (3754.9 h)	-2130	-262	49	94	15	2227	0
During cooling (4066.4 h)	-796	4122	131	251	32	0	-3731
Rest of time	-300	218	24	46	7	0	1

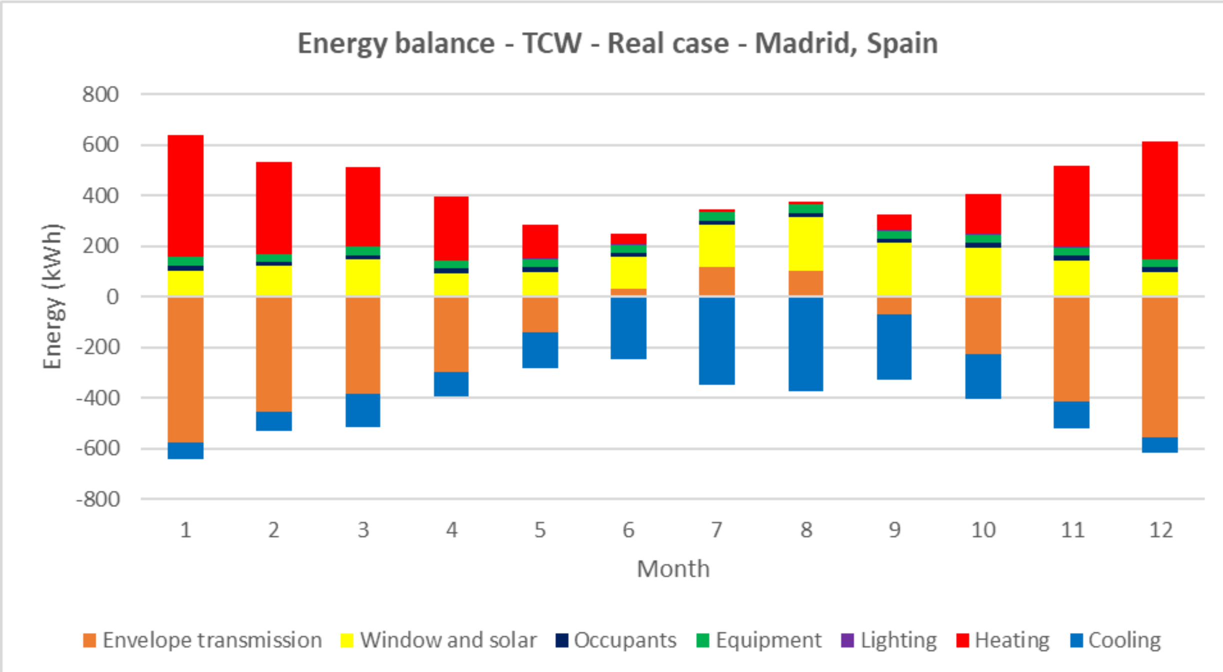

Fig.82. Energy balance - TCW - Real case - Madrid, Spain. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 54. Energy balance - TCW - Real case - Madrid, Spain. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - TCW - Real case - Madrid, spain (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-576	104	18	35	2	482	-64
2	-453	122	16	30	2	363	-79
3	-384	148	17	33	2	314	-129
4	-295	95	17	32	2	249	-98
5	-139	98	18	35	2	132	-145
6	32	126	16	32	1	40	-248
7	117	166	17	33	2	12	-348
8	101	212	18	35	2	7	-375
9	-68	215	16	30	2	63	-258
10	-228	194	18	35	2	156	-177
11	-415	145	17	33	2	322	-103
12	-555	99	17	32	2	467	-60
Total	**-2863**	**1722**	**205**	**392**	**22**	**2606**	**-2082**
During heating (4355.6 h)	-2321	-514	71	135	21	2606	0
During cooling (3529.0 h)	-334	2090	114	218	1	0	-2081
Rest of time	-207	146	20	39	1	0	0

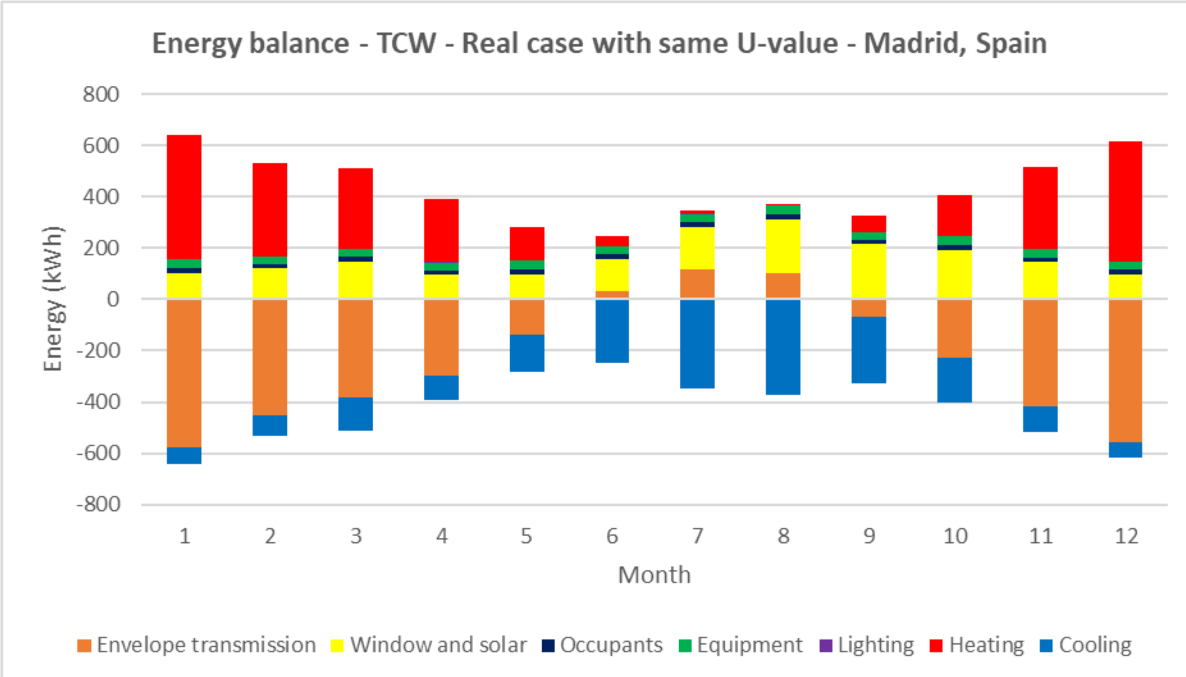

Fig.83. Energy balance - TCW - Real case with same U-value - Madrid, Spain. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 55. Energy balance - TCW - Real case with same U-value - Madrid, Spain. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - TCW - Real case with same U-value - Madrid, spain (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-576	104	18	35	2	482	-64
2	-453	122	16	30	2	363	-79
3	-384	148	17	33	2	314	-129
4	-295	95	17	32	2	249	-98
5	-139	98	18	35	2	132	-145
6	32	126	16	32	1	40	-248
7	117	166	17	33	2	12	-348
8	101	212	18	35	2	7	-375
9	-68	215	16	30	2	63	-258
10	-228	194	18	35	2	156	-177
11	-415	145	17	33	2	322	-103
12	-555	99	17	32	2	467	-60
Total	**-2863**	**1722**	**205**	**392**	**22**	**2606**	**-2082**
During heating (4355.6 h)	-2321	-514	71	135	21	2606	0
During cooling (3529 h)	-334	2090	114	218	1	0	-2081
Rest of time	-207	146	20	39	1	0	0

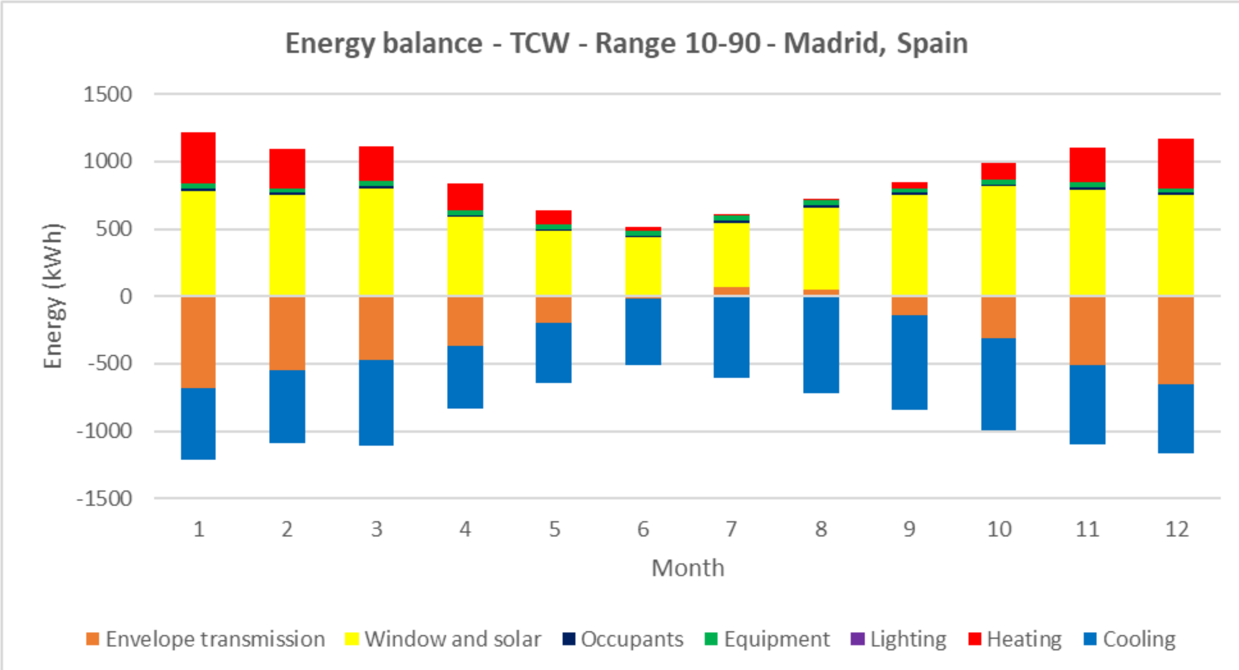

Fig.84. Energy balance - TCW - Range 10-90 - Madrid, Spain. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 56. Energy balance - TCW - Range 10-90 - Madrid, Spain. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - TCW - Range 10-90 - Madrid, spain (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-680	783	18	35	2	382	-538
2	-547	756	15	30	1	292	-548
3	-477	804	17	33	1	254	-633
4	-371	586	16	32	1	201	-465
5	-200	482	18	35	1	104	-440
6	-15	434	16	32	1	30	-498
7	73	475	17	33	1	8	-608
8	51	609	18	35	1	4	-719
9	-137	751	16	30	1	50	-711
10	-313	814	18	35	2	123	-679
11	-510	793	17	33	1	259	-593
12	-658	750	16	32	1	366	-508
Total	**-3784**	**8035**	**202**	**392**	**15**	**2071**	**-6938**
During heating (3539 h)	-2005	-226	48	93	14	2071	0
During cooling (4449.2 h)	-1522	8050	140	271	0	0	-6936
Rest of time	-257	212	15	28	1	0	-1

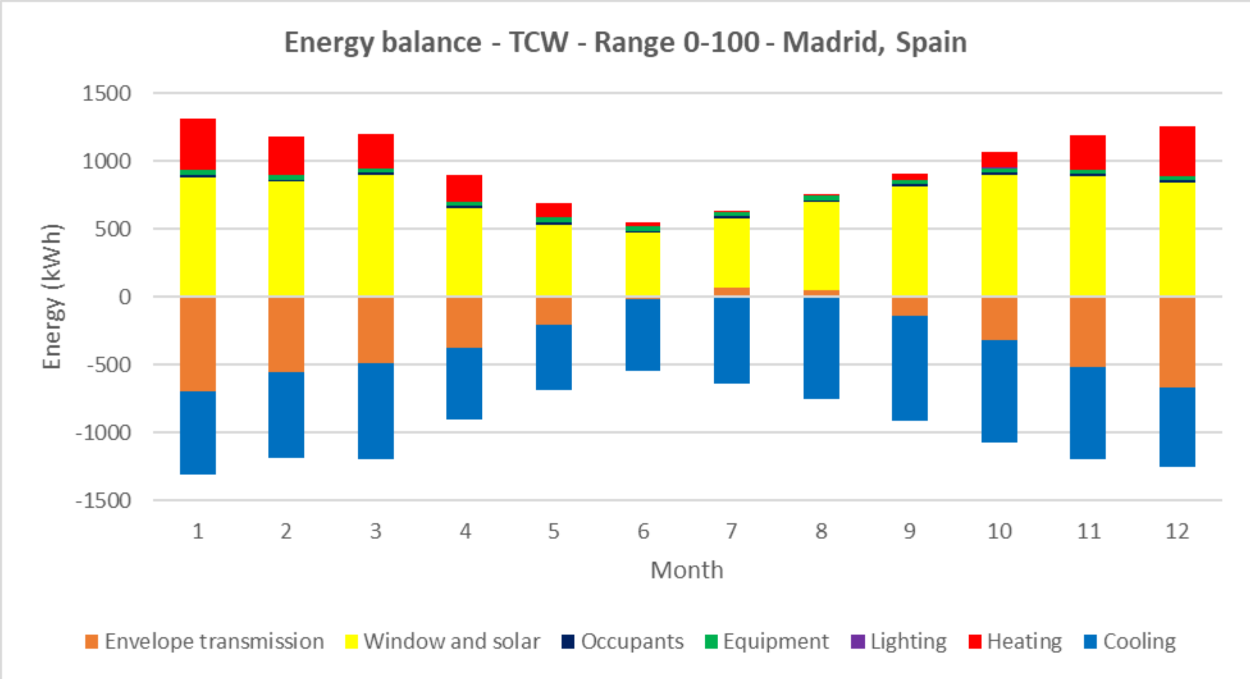

Fig.85. Energy balance - TCW - Range 0-100 - Madrid, Spain.Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 57. Energy balance - TCW - Range 0-100 - Madrid, Spain.Each category is presented per month and during heating, cooling and rest of time.

Energy balance - TCW - Range 0-100 - Madrid, spain (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-692	881	18	35	2	377	-619
2	-556	850	15	30	1	287	-628
3	-486	897	17	33	1	250	-712
4	-378	653	16	32	1	198	-522
5	-206	532	18	35	1	103	-482
6	-19	470	16	32	0	29	-529
7	68	507	17	33	1	8	-635
8	47	649	18	35	1	4	-755
9	-143	816	15	30	1	49	-769
10	-320	898	18	35	2	120	-752
11	-520	887	17	33	1	256	-674
12	-669	843	16	32	1	361	-584
Total	**-3876**	**8883**	**201**	**392**	**14**	**2041**	**-7661**
During heating (3479.5 h)	-1975	-222	47	89	13	2041	0
During cooling (4523 h)	-1649	8897	141	276	0	0	-7661
Rest of time	-252	208	14	26	1	0	0

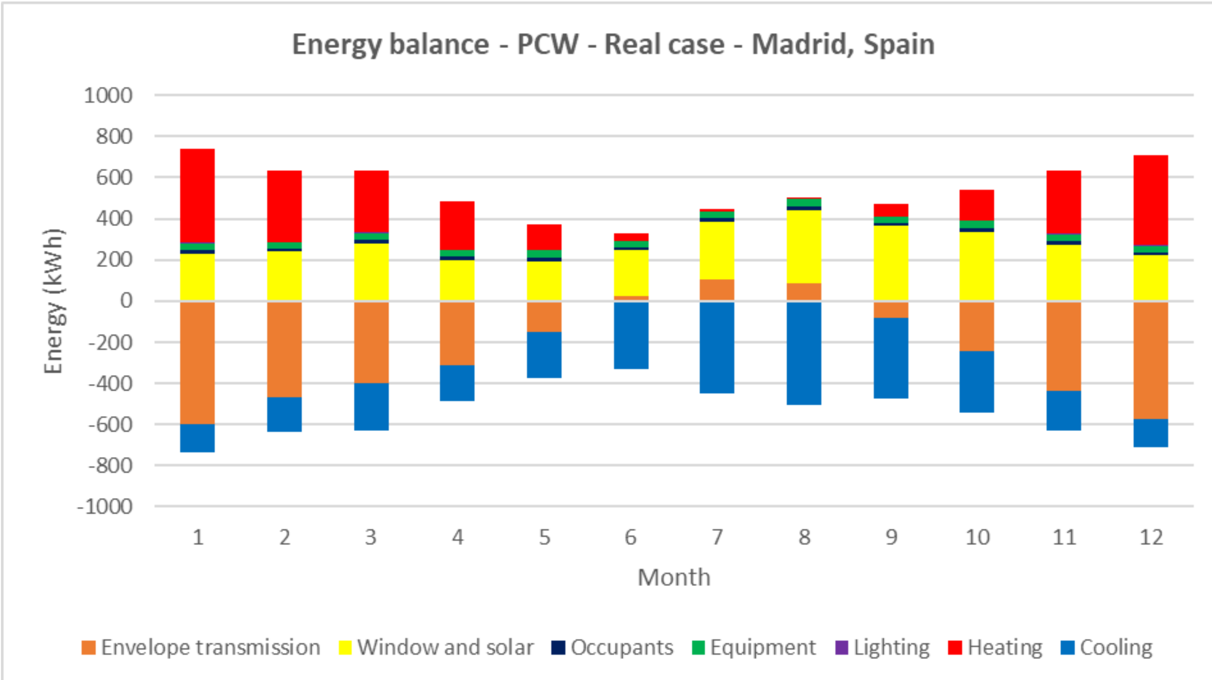

Fig.86. Energy balance - PCW - Real case - Madrid, Spain. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 58. Energy balance - PCW - Real case - Madrid, Spain. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - PCW - Real case - Madrid, spain (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-596	228	18	35	2	456	-141
2	-470	241	16	30	2	345	-163
3	-402	282	17	33	1	299	-231
4	-310	198	16	32	2	238	-176
5	-151	194	18	35	1	125	-223
6	21	224	16	32	1	37	-332
7	106	280	17	33	1	11	-449
8	89	354	18	35	2	6	-504
9	-84	365	16	30	2	61	-390
10	-247	337	18	35	2	150	-295
11	-434	275	17	33	2	305	-197
12	-575	220	17	32	2	440	-134
Total	**-3052**	**3200**	**204**	**392**	**19**	**2472**	**-3235**
During heating (4053.5 h)	-2166	-502	60	114	18	2472	0
During cooling (3863.7 h)	-681	3556	125	241	0	0	-3233
Rest of time	-205	146	19	36	1	0	-1

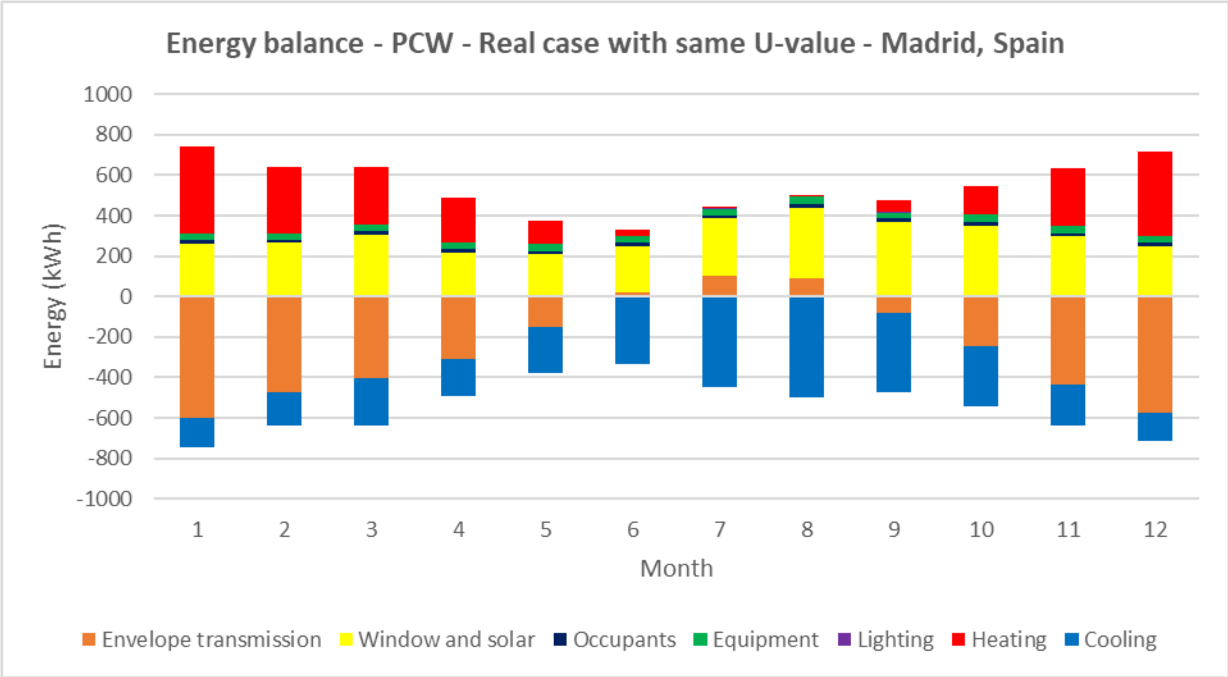

Fig.87. Energy balance - PCW - Real case with same U-value - Madrid, Spain. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 59. Energy balance - PCW - Real case with same U-value - Madrid, Spain. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - PCW - Real case with same U-value - Madrid, spain (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-598	258	18	35	2	432	-146
2	-472	265	16	30	2	327	-167
3	-403	304	17	33	1	283	-235
4	-311	218	16	32	2	224	-180
5	-153	207	18	35	1	117	-225
6	21	228	16	32	1	34	-333
7	105	279	17	33	1	10	-447
8	88	353	18	35	2	5	-500
9	-84	370	16	30	2	56	-390
10	-247	351	18	35	2	140	-298
11	-435	296	17	33	1	289	-201
12	-577	248	17	32	2	417	-137
Total	**-3067**	**3377**	**204**	**392**	**19**	**2333**	**-3257**
During heating (3994.9 h)	-2151	-374	58	112	17	2333	0
During cooling (3918.5 h)	-703	3594	127	244	0	0	-3258
Rest of time	-213	156	19	36	1	0	1

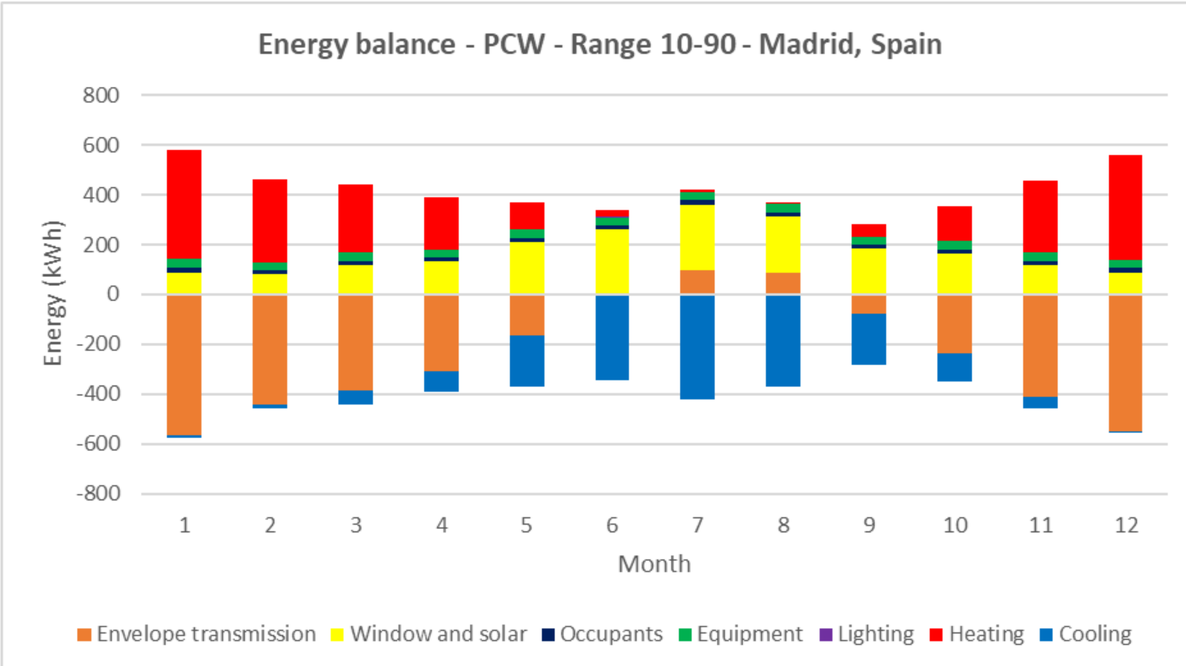

Fig.88. Energy balance - PCW - Range 10-90 - Madrid, Spain. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 60. Energy balance - PCW - Range 10-90 - Madrid, Spain. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - PCW - Range 10-90 - Madrid, spain (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-568	88	19	35	2	436	-10
2	-442	81	16	30	2	332	-17
3	-384	117	17	33	1	274	-59
4	-309	131	17	32	1	210	-82
5	-167	210	18	35	1	108	-204
6	6	257	16	32	1	30	-342
7	95	265	17	33	1	8	-421
8	87	223	18	35	1	5	-370
9	-77	184	16	30	1	54	-208
10	-236	164	18	35	2	134	-116
11	-412	117	18	33	1	289	-45
12	-548	89	17	32	2	419	-9
Total	**-2954**	**1925**	**207**	**392**	**15**	**2297**	**-1883**
During heating (4076 h)	-2329	-170	64	121	14	2297	0
During cooling (3634.6 h)	-265	1819	114	217	0	0	-1883
Rest of time	-359	277	29	54	1	0	0

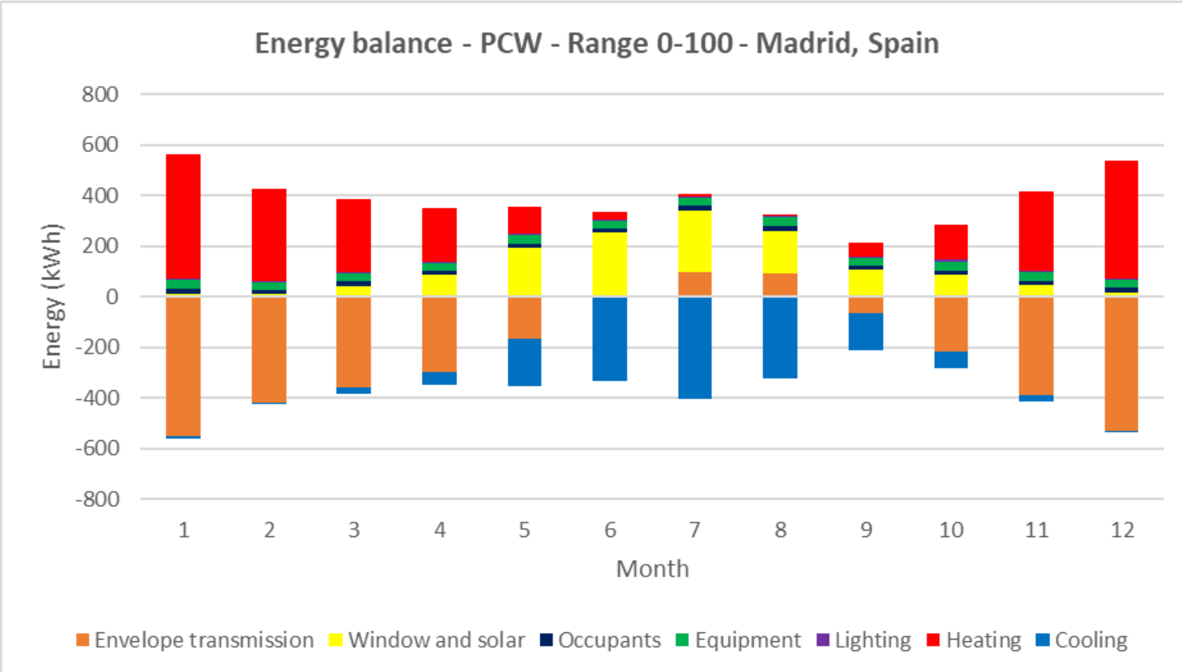

Fig.89. Energy balance - PCW - Range 0-100 - Madrid, Spain. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 61. Energy balance - PCW - Range 0-100 - Madrid, Spain. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - PCW - Range 0-100 - Madrid, spain (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-551	13	19	35	6	490	-11
2	-417	10	16	30	6	364	-9
3	-359	42	18	33	7	285	-25
4	-296	86	17	32	5	210	-53
5	-164	193	18	35	3	106	-191
6	6	248	16	32	2	30	-334
7	98	244	17	33	3	8	-405
8	95	167	18	35	6	5	-325
9	-63	108	16	30	6	54	-151
10	-218	86	18	35	7	136	-65
11	-387	45	18	33	6	315	-29
12	-530	18	17	32	6	466	-8
Total	**-2788**	**1260**	**208**	**392**	**63**	**2469**	**-1605**
During heating (4512.2 h)	-2461	-281	84	156	30	2469	0
During cooling (3248 h)	-40	1336	97	186	26	0	-1605
Rest of time	-287	205	27	50	6	0	0

A.4.6 Energy balance Nairobi, Kenya

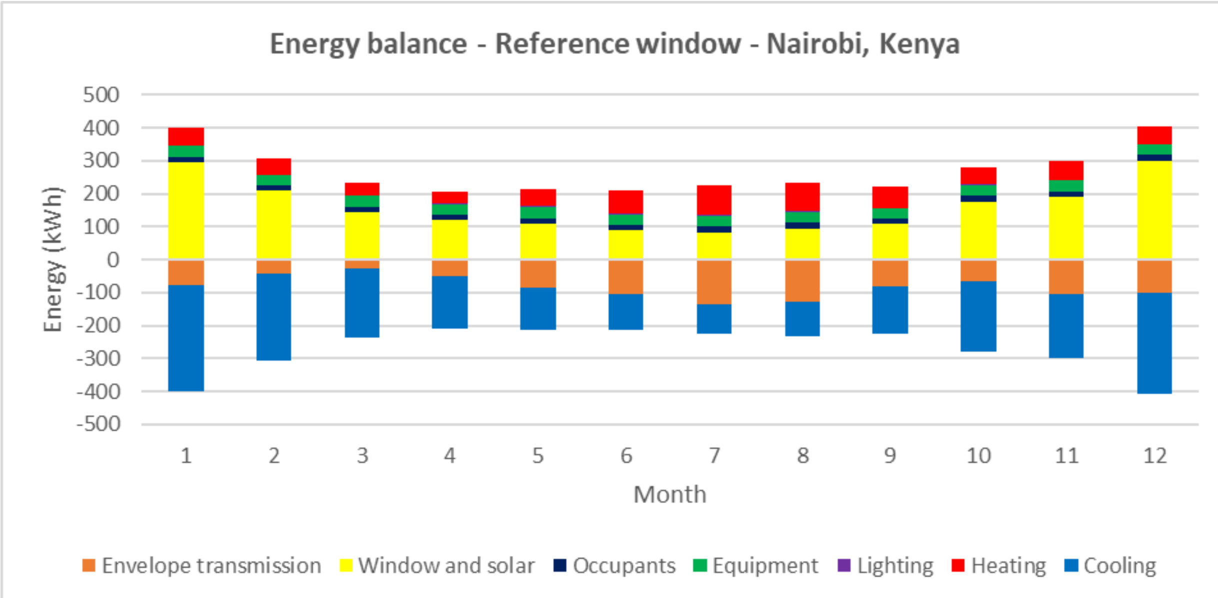

Fig.90. Energy balance - Reference window - Nairobi, Kenya. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 62. Energy balance - Reference window - Nairobi, Kenya. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - Reference window - Nairobi, Kenya (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-78	295	18	35	0	52	-322
2	-43	210	16	30	0	49	-263
3	-27	143	17	33	1	41	-208
4	-51	120	16	32	1	37	-156
5	-87	108	18	35	1	51	-127
6	-105	89	16	32	1	73	-107
7	-135	83	17	33	2	89	-90
8	-127	93	18	35	1	84	-105
9	-82	109	16	30	1	67	-141
10	-64	175	18	35	1	51	-216
11	-103	190	17	33	0	58	-196
12	-101	301	16	32	0	55	-304
Total	**-1001**	**1914**	**204**	**392**	**9**	**708**	**-2235**
During heating (3560.3 h)	-728	-114	40	77	9	708	0
During cooling (4116.2 h)	-112	1928	144	278	0	0	-2236
Rest of time	-161	100	19	37	0	0	0

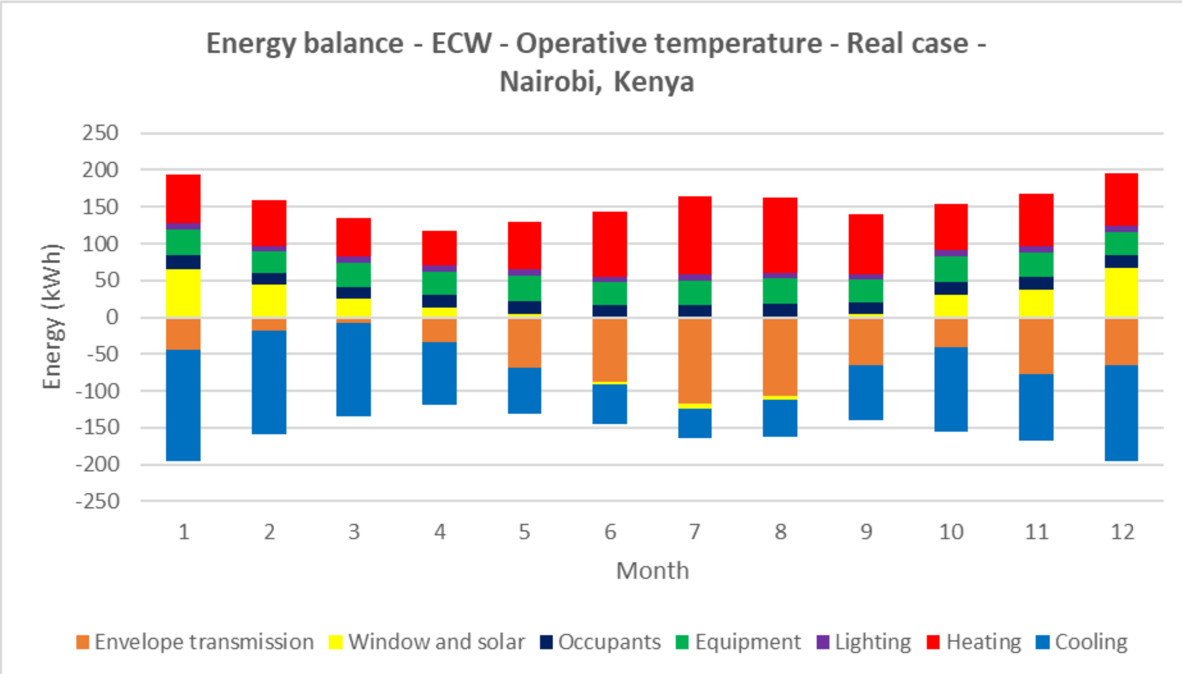

Fig.91. Energy balance - ECW - Operative temperature - Real case - Nairobi, Kenya. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 63. Energy balance - ECW - Operative temperature - Real case - Nairobi, Kenya.Each category is presented per month and during heating, cooling and rest of time.

Energy balance - ECW - Operative temperature - Real case - Nairobi, Kenya (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-43	66	18	35	9	66	-152
2	-18	44	16	30	8	61	-142
3	-8	25	17	33	9	51	-127
4	-33	14	16	32	8	48	-85
5	-68	4	18	35	9	65	-63
6	-88	-3	17	32	7	89	-53
7	-118	-6	17	33	7	107	-41
8	-107	-5	18	35	8	101	-51
9	-65	5	16	30	7	82	-75
10	-40	30	18	35	9	63	-115
11	-77	38	17	33	8	71	-92
12	-65	68	16	32	8	71	-131
Total	**-730**	**279**	**204**	**392**	**96**	**875**	**-1125**
During heating (3708.9 h)	-774	-232	38	73	14	876	0
During cooling (3850.2 h)	226	394	144	276	82	0	-1125
Rest of time	-183	117	22	42	0	0	0

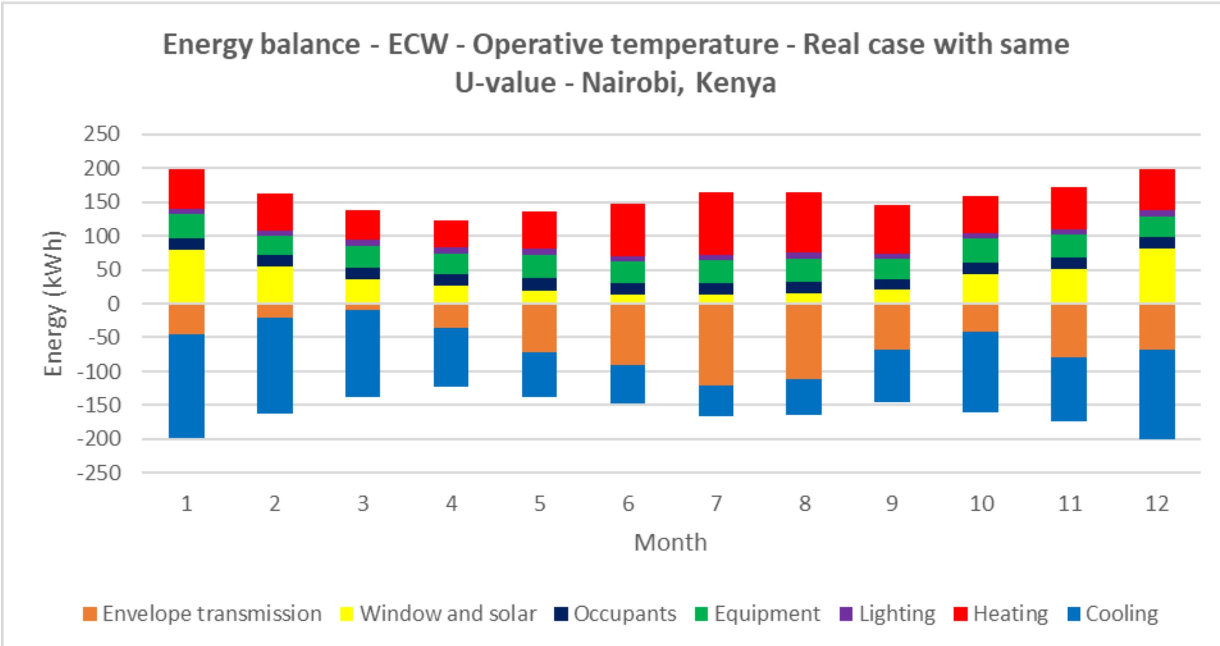

Fig.92. Energy balance - ECW - Operative temp - Real case with same U-value - Nairobi, Kenya. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 64. Energy balance - ECW - Operative temp - Real case with same U-value - Nairobi, Kenya. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - ECW Operative temp - Real case with same U-value - Nairobi, Kenya (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-46	79	18	35	9	57	-153
2	-21	55	16	30	8	53	-142
3	-10	36	17	33	9	44	-129
4	-35	27	16	32	8	40	-88
5	-71	20	18	35	9	56	-67
6	-91	14	17	32	7	77	-56
7	-122	14	17	33	7	94	-44
8	-111	15	18	35	8	89	-54
9	-68	21	16	30	7	71	-78
10	-42	44	18	35	9	54	-118
11	-80	51	17	33	8	62	-94
12	-67	81	16	32	8	61	-133
Total	**-762**	**456**	**204**	**392**	**97**	**757**	**-1156**
During heating (3589.1 h)	-761	-123	37	70	14	758	0
During cooling (3947.7 h)	200	443	146	280	83	0	-1155
Rest of time	-202	137	22	41	0	0	0

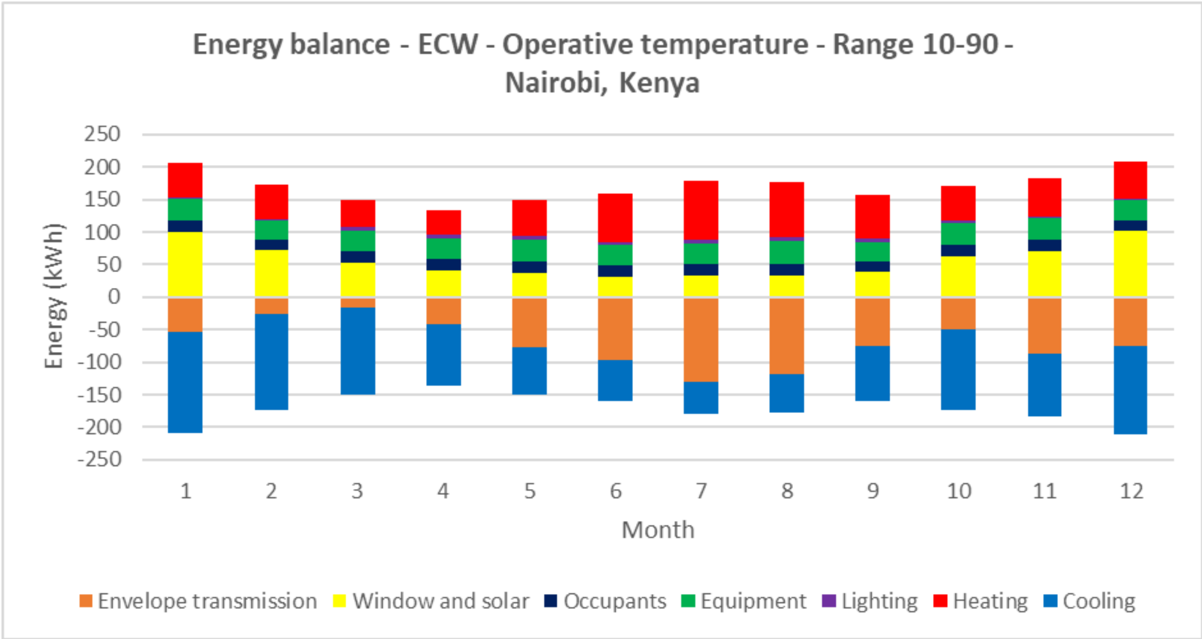

Fig.93. Energy balance - ECW - Operative temperature - Range 10-90 - Nairobi, Kenya. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 65. Energy balance - ECW - Operative temperature - Range 10-90 - Nairobi, Kenya. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - ECW - Operative temperature - Range 10-90 - Nairobi, Kenya [(kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-54	99	18	35	1	55	-155
2	-27	73	16	30	2	52	-147
3	-15	53	17	33	5	42	-135
4	-42	42	16	32	6	39	-94
5	-78	36	18	35	6	54	-73
6	-98	32	17	32	5	75	-63
7	-130	33	17	33	6	90	-50
8	-119	33	18	35	6	86	-60
9	-74	39	16	30	5	68	-85
10	-50	62	18	35	4	53	-123
11	-87	71	17	33	3	58	-97
12	-76	101	16	32	1	58	-135
Total	**-848**	**672**	**204**	**392**	**50**	**729**	**-1215**
During heating (3434.4 h)	-782	-51	31	59	8	729	0
During cooling (4153.2 h)	208	505	154	296	43	0	-1215
Rest of time	-274	218	19	37	0	0	0

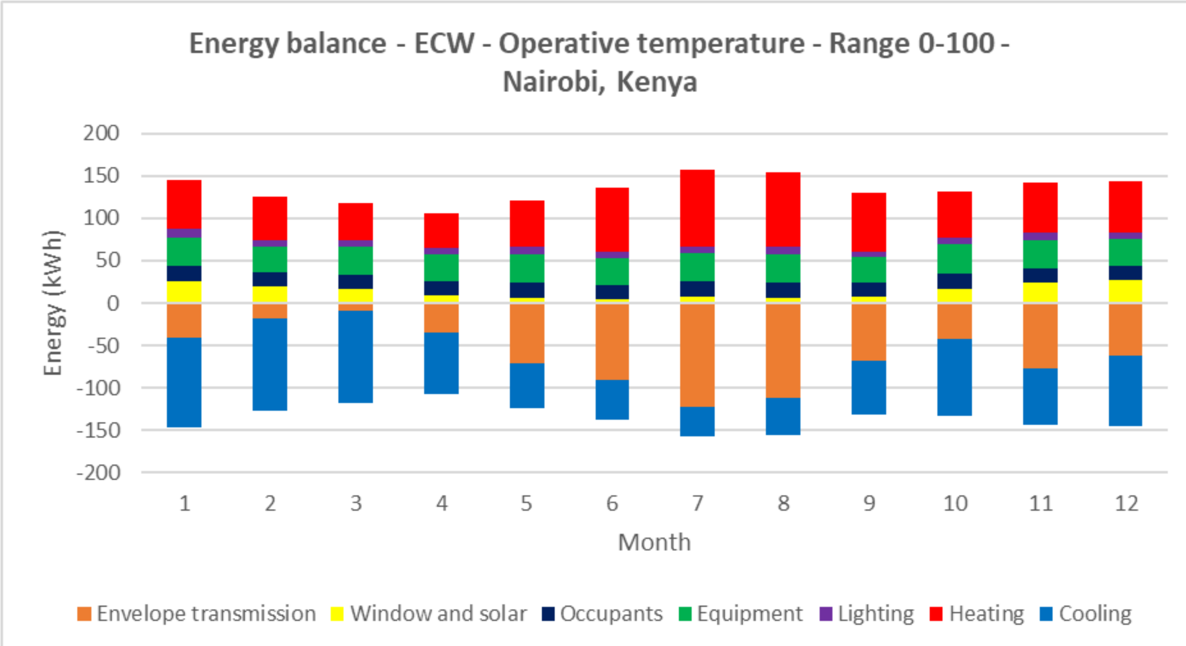

Fig.94. Energy balance - ECW - Operative temperature - Range 0-100 - Nairobi, Kenya. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 66. Energy balance - ECW - Operative temperature - Range 0-100 - Nairobi, Kenya. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - ECW - Operative temperature - Range 0-100 - Nairobi, Kenya (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-42	25	18	35	9	57	-105
2	-18	20	16	30	8	52	-110
3	-9	16	17	33	8	43	-109
4	-35	10	16	32	8	40	-72
5	-71	6	18	35	8	55	-53
6	-91	5	17	32	7	76	-45
7	-123	8	17	33	8	92	-35
8	-111	6	18	35	8	88	-44
9	-68	8	16	30	7	70	-64
10	-42	16	18	35	9	54	-92
11	-78	24	17	33	9	60	-66
12	-62	27	16	32	9	60	-84
Total	**-750**	**170**	**204**	**392**	**98**	**749**	**-876**
During heating (3490.5 h)	-801	-49	30	57	8	749	0
During cooling (4091.7 h)	325	-3	157	300	91	0	-876
Rest of time	-274	222	18	35	0	0	0

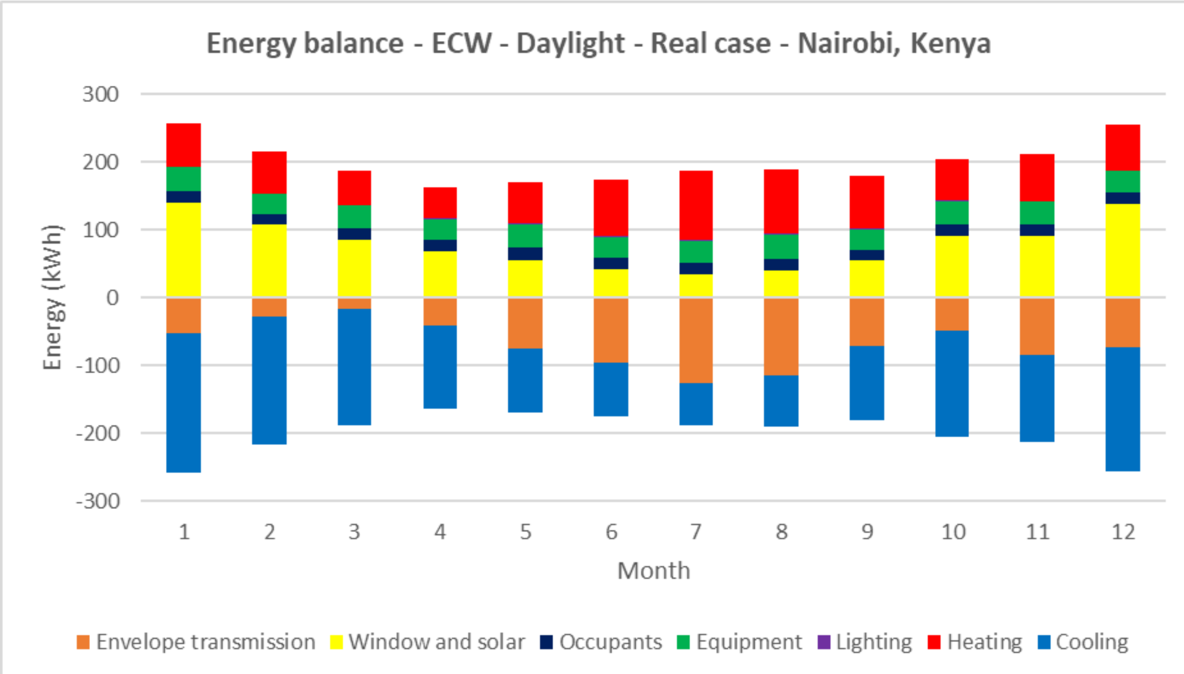

Fig.95. Energy balance - ECW - Daylight - Real case - Nairobi, Kenya. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 67. Energy balance - ECW - Daylight - Real case - Nairobi, Kenya. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - ECW - Daylight - Real case - Nairobi, Kenya (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-53	140	18	35	0	65	-205
2	-27	108	16	30	0	61	-189
3	-16	86	17	33	1	50	-171
4	-41	68	16	32	2	45	-122
5	-76	56	18	35	2	60	-94
6	-95	42	17	32	2	83	-80
7	-125	34	17	33	2	102	-63
8	-115	40	18	35	2	95	-74
9	-71	54	16	30	2	78	-108
10	-48	90	18	35	1	61	-157
11	-85	92	17	33	0	70	-128
12	-74	139	16	32	0	68	-182
Total	**-826**	**949**	**204**	**392**	**14**	**837**	**-1573**
During heating (3756.8 h)	-775	-214	43	83	14	837	0
During cooling (3865.8 h)	99	1084	136	262	0	0	-1573
Rest of time	-150	79	25	47	0	0	0

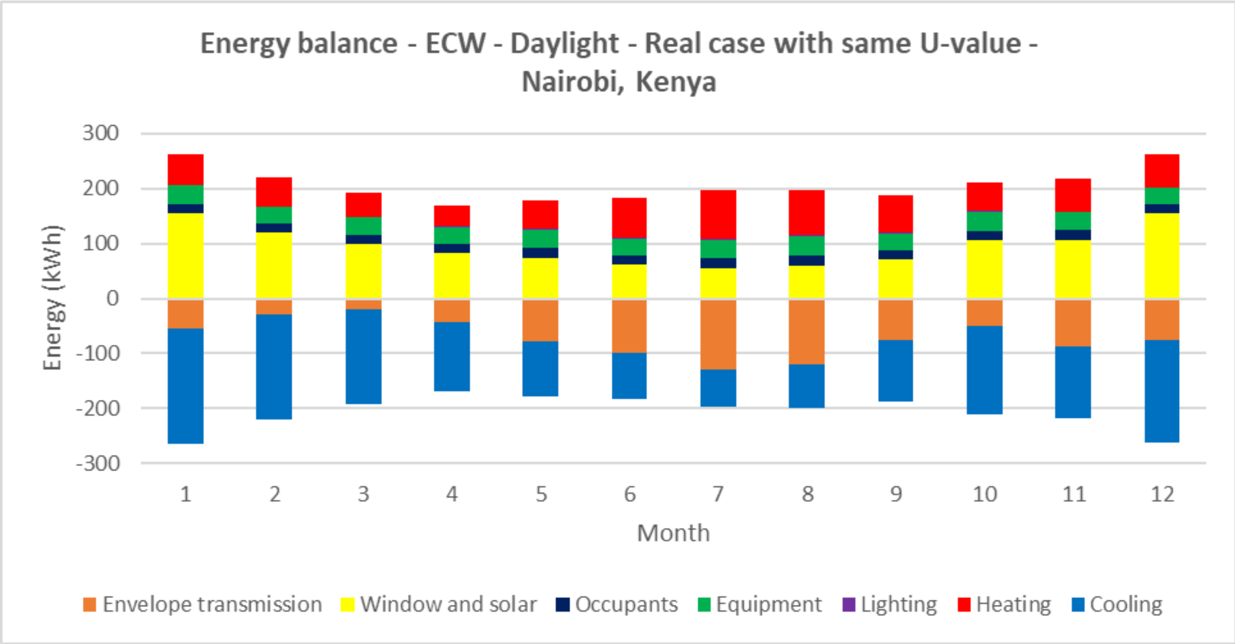

Fig.96. Energy balance - ECW - Daylight - Real case with same U-value - Nairobi, Kenya. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 68. Energy balance - ECW - Daylight - Real case with same U-value - Nairobi, Kenya. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - ECW - Daylight - Real case with same U-value - Nairobi, Kenya (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-56	154	18	35	0	56	-208
2	-29	121	16	30	0	53	-190
3	-19	98	17	33	1	42	-173
4	-44	82	16	32	2	38	-126
5	-79	73	18	35	2	51	-100
6	-98	61	16	32	2	72	-85
7	-129	55	17	33	2	88	-68
8	-119	61	18	35	2	82	-79
9	-75	72	16	30	2	68	-112
10	-51	105	18	35	1	52	-160
11	-87	107	17	33	0	60	-131
12	-76	154	16	32	0	59	-185
Total	**-861**	**1143**	**204**	**392**	**14**	**722**	**-1616**
During heating (3604.4 h)	-765	-102	41	79	14	722	0
During cooling (3960.1 h)	80	1143	138	265	0	0	-1616
Rest of time	-175	102	25	48	0	0	0

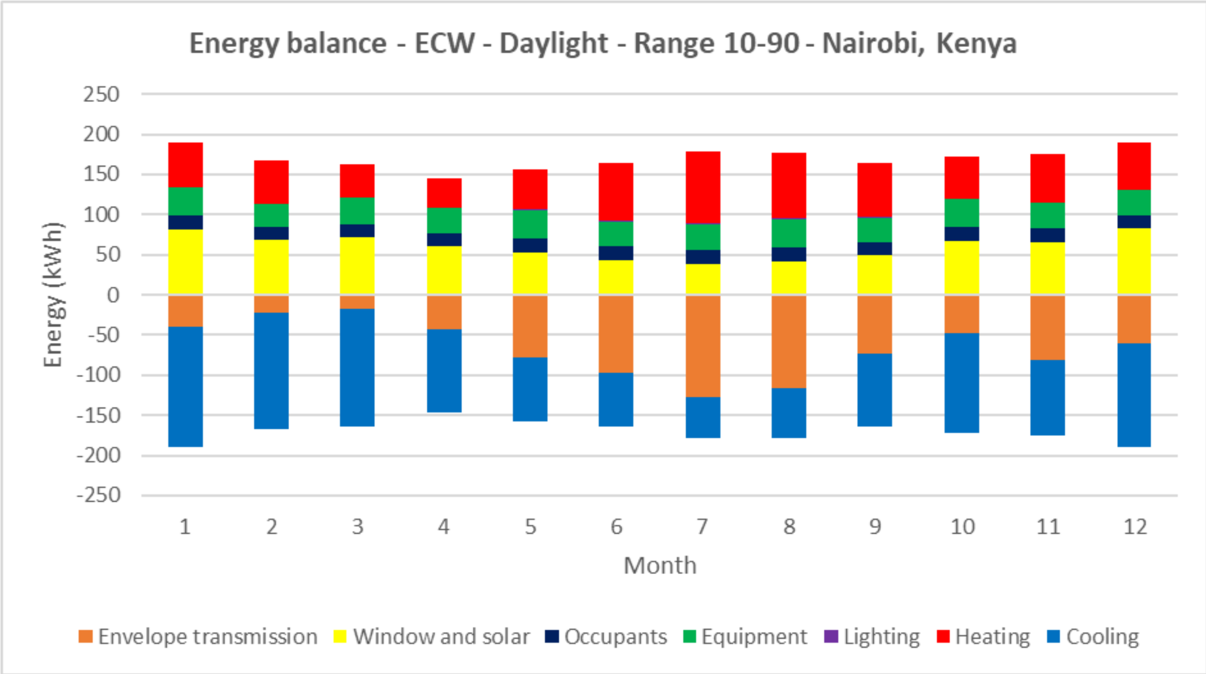

Fig.97. Energy balance - ECW - Daylight - Range 10-90 - Nairobi, Kenya. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 69. Energy balance - ECW - Daylight - Range 10-90 - Nairobi, Kenya. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - ECW - Daylight - Range 10-90 - Nairobi, Kenya (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-40	81	18	35	0	56	-150
2	-23	68	16	30	0	53	-145
3	-18	71	17	33	0	42	-146
4	-43	60	16	32	1	37	-103
5	-79	53	18	35	1	50	-78
6	-97	43	17	32	1	71	-67
7	-127	38	17	33	1	88	-51
8	-117	41	18	35	1	82	-61
9	-73	50	16	30	1	67	-91
10	-48	67	18	35	1	52	-125
11	-82	65	17	33	0	60	-95
12	-61	83	16	32	0	59	-129
Total	**-807**	**721**	**204**	**392**	**8**	**717**	**-1240**
During heating (3682.7 h)	-798	-67	44	84	8	717	0
During cooling (3817.2 h)	147	717	131	252	0	0	-1240
Rest of time	-156	71	29	56	0	0	0

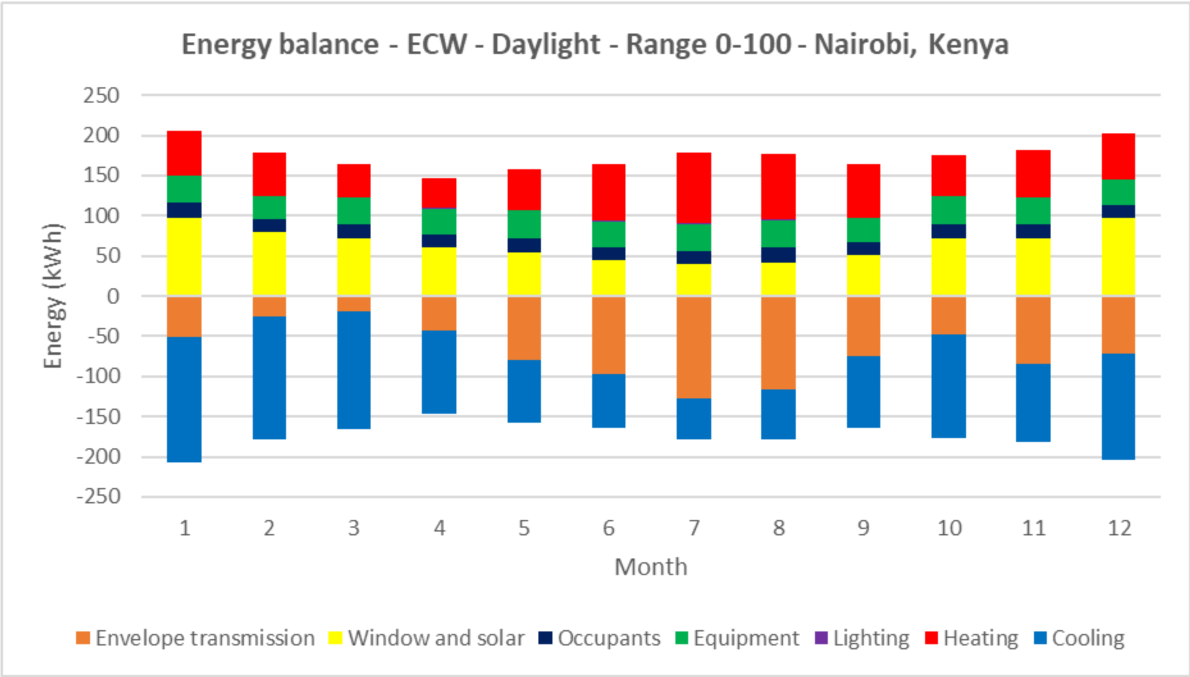

Fig.98. Energy balance - ECW - Daylight - Range 0-100 - Nairobi, Kenya. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 70. Energy balance - ECW - Daylight - Range 0-100 - Nairobi, Kenya. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - ECW - Daylight - Range 0-100 - Nairobi, Kenya (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-51	98	18	35	0	55	-156
2	-26	80	16	30	0	53	-153
3	-18	72	17	33	0	42	-147
4	-44	61	16	32	1	37	-103
5	-79	54	18	35	1	50	-79
6	-98	44	17	32	1	71	-67
7	-127	39	17	33	1	87	-52
8	-117	42	18	35	1	81	-62
9	-74	51	16	30	1	67	-90
10	-49	71	18	35	1	52	-128
11	-85	72	17	33	0	59	-97
12	-71	97	16	32	0	57	-132
Total	**-838**	**781**	**204**	**392**	**7**	**711**	**-1265**
During heating (3658.9 h)	-798	-58	43	82	7	711	0
During cooling (3855.8 h)	116	766	133	255	0	0	-1265
Rest of time	-156	73	28	54	0	0	0

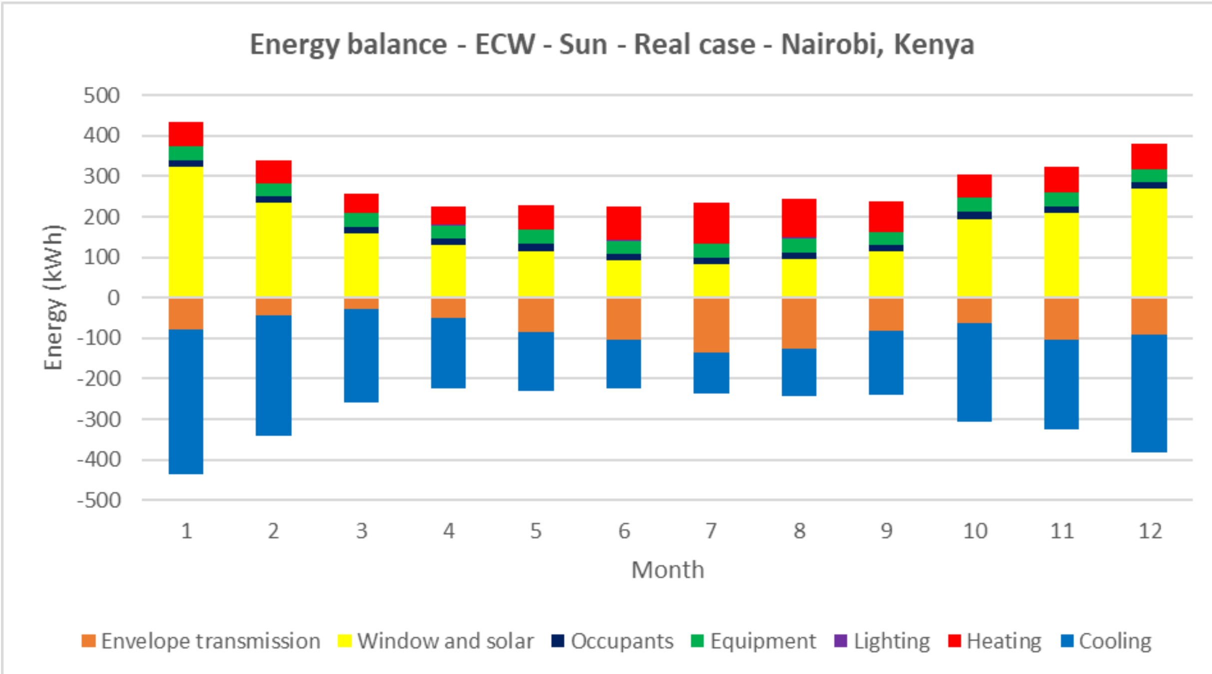

Fig.99. Energy balance - ECW - Sun - Real case - Nairobi, Kenya. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 71. Energy balance - ECW - Sun - Real case - Nairobi, Kenya. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - ECW - Sun - Real case - Nairobi, Kenya (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-77	323	18	35	0	60	-360
2	-43	236	16	30	0	57	-296
3	-27	159	17	33	1	48	-231
4	-51	131	16	32	2	44	-174
5	-86	114	18	35	2	59	-143
6	-104	92	16	32	2	82	-120
7	-135	83	17	33	2	101	-101
8	-126	95	18	35	2	95	-118
9	-83	115	16	30	2	77	-157
10	-64	194	18	35	1	59	-243
11	-102	210	17	33	0	65	-224
12	-92	269	16	32	2	64	-291
Total	**-990**	**2019**	**203**	**392**	**16**	**809**	**-2459**
During heating (3624.3 h)	-714	-229	38	73	14	809	0
During cooling (4132.1 h)	-142	2171	147	284	2	0	-2459
Rest of time	-135	78	18	35	0	0	0

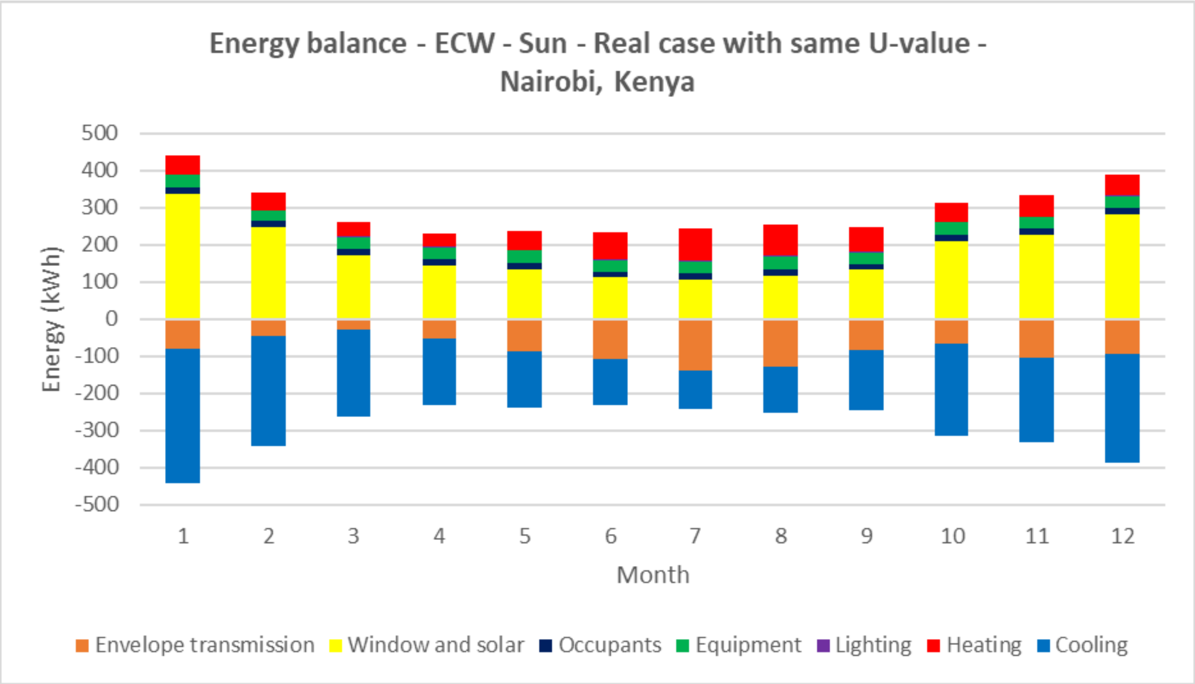

Fig.100. Energy balance - ECW - Sun - Real case with same U-value - Nairobi, Kenya. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 72. Energy balance - ECW - Sun - Real case with same U-value - Nairobi, Kenya. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - ECW - Sun - Real case with same U-value - Nairobi, Kenya (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-79	337	18	35	1	51	-363
2	-45	247	16	30	0	49	-299
3	-30	171	17	33	1	40	-233
4	-54	145	16	32	2	37	-179
5	-89	132	18	35	2	50	-149
6	-107	111	16	32	2	72	-126
7	-138	105	17	33	2	87	-106
8	-130	116	18	35	2	82	-124
9	-85	133	16	30	2	66	-162
10	-66	209	18	35	1	50	-248
11	-106	225	17	33	0	56	-228
12	-94	283	16	32	2	54	-295
Total	**-1021**	**2214**	**203**	**392**	**16**	**694**	**-2509**
During heating (3485.7 h)	-703	-121	36	70	14	693	0
During cooling (4223.9 h)	-161	2236	148	286	2	0	-2509
Rest of time	-157	98	19	36	0	0	0

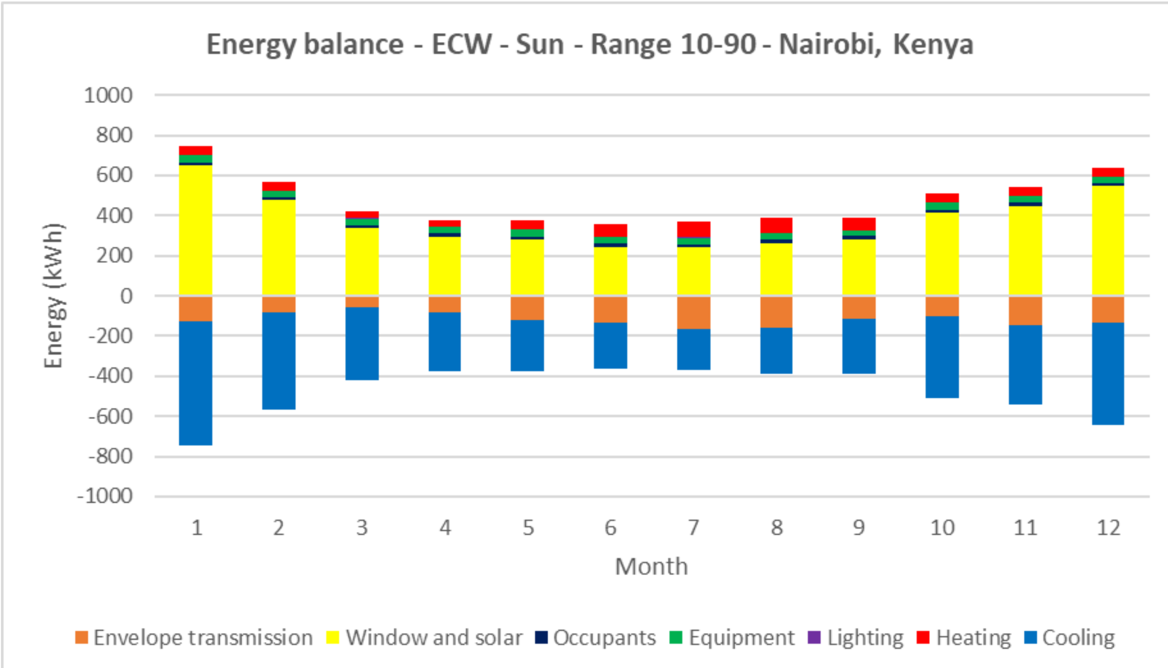

Fig.101. Energy balance - ECW - Sun - Range 10-90 - Nairobi, Kenya. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 73. Energy balance - ECW - Sun - Range 10-90 - Nairobi, Kenya. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - ECW - Sun - Range 10-90 - Nairobi, Kenya (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-127	648	18	35	0	45	-620
2	-82	479	16	30	0	43	-487
3	-58	336	17	33	0	36	-365
4	-82	294	16	32	1	32	-295
5	-118	278	18	35	1	46	-261
6	-135	246	16	32	1	66	-226
7	-168	240	17	33	1	80	-205
8	-159	260	18	35	1	76	-231
9	-113	282	16	30	1	61	-277
10	-102	412	18	35	1	46	-410
11	-143	445	17	33	0	48	-402
12	-133	547	16	32	0	46	-509
Total	**-1419**	**4466**	**203**	**392**	**8**	**624**	**-4287**
During heating (3181.2 h)	-693	-38	30	59	8	624	0
During cooling (4586.6 h)	-538	4364	158	304	0	0	-4286
Rest of time	-188	140	15	29	0	0	-1

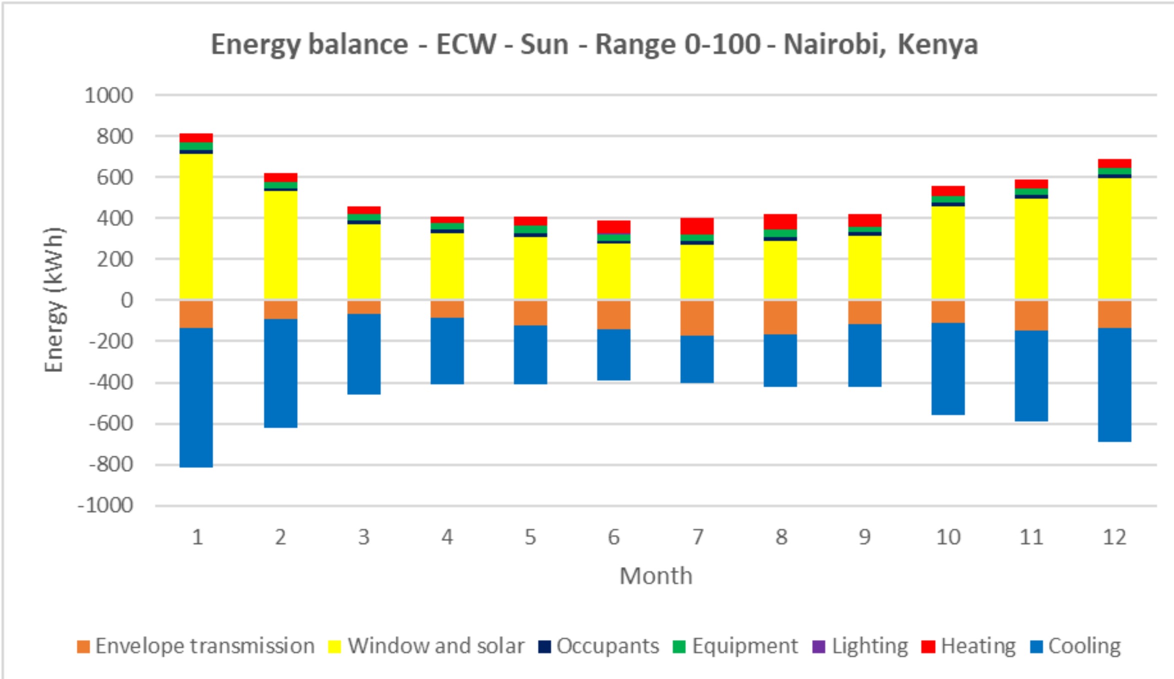

Fig.102. Energy balance - ECW - Sun - Range 0-100 - Nairobi, Kenya. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 74. Energy balance - ECW - Sun - Range 0-100 - Nairobi, Kenya. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - ECW - Sun - Range 0-100 - Nairobi, Kenya (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-134	715	18	35	0	43	-678
2	-88	531	16	30	0	43	-533
3	-63	373	17	33	0	35	-396
4	-86	327	16	32	1	32	-323
5	-123	312	18	35	1	45	-288
6	-139	276	16	32	1	65	-251
7	-173	271	17	33	1	79	-228
8	-165	293	18	35	1	75	-257
9	-118	315	16	30	1	60	-304
10	-108	458	18	35	1	45	-449
11	-150	495	17	33	0	47	-443
12	-137	598	16	32	2	45	-555
Total	**-1487**	**4964**	**203**	**392**	**9**	**612**	**-4705**
During heating (3132.5 h)	-685	-31	29	56	8	612	0
During cooling (4655.3 h)	-619	4858	160	308	2	0	-4706
Rest of time	-183	136	14	27	0	0	0

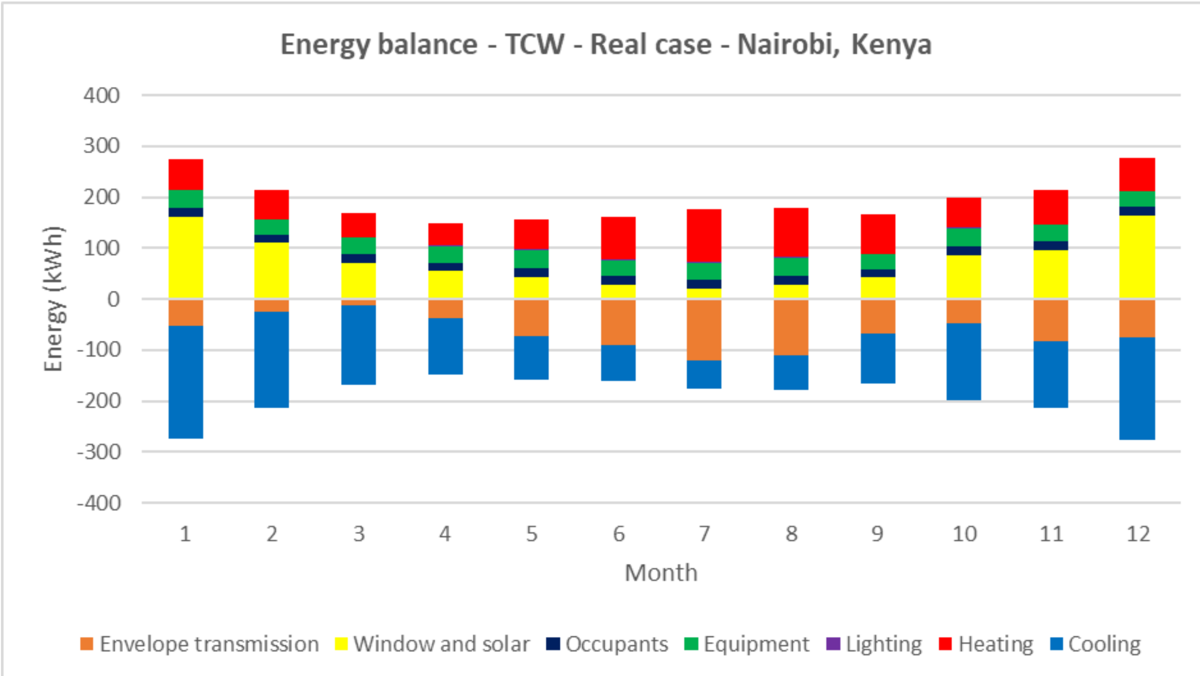

Fig.103. Energy balance - TCW - Real case - Nairobi, Kenya. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 75. Energy balance - TCW - Real case - Nairobi, Kenya. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - TCW - Real case - Nairobi, Kenya (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-54	161	18	35	0	61	-222
2	-26	110	16	30	0	57	-188
3	-13	70	17	33	1	47	-156
4	-38	55	16	32	2	43	-111
5	-72	43	18	35	2	59	-85
6	-91	29	17	32	2	82	-70
7	-120	21	17	33	2	103	-56
8	-111	29	18	35	2	95	-67
9	-68	42	16	30	2	76	-97
10	-47	87	18	35	1	58	-153
11	-83	96	17	33	0	67	-131
12	-75	164	16	32	0	64	-203
Total	**-797**	**906**	**204**	**392**	**15**	**813**	**-1539**
During heating (3818.9 h)	-732	-233	44	85	15	813	0
During cooling (3822.4 h)	61	1084	137	263	0	0	-1539
Rest of time	-125	56	23	44	0	0	0

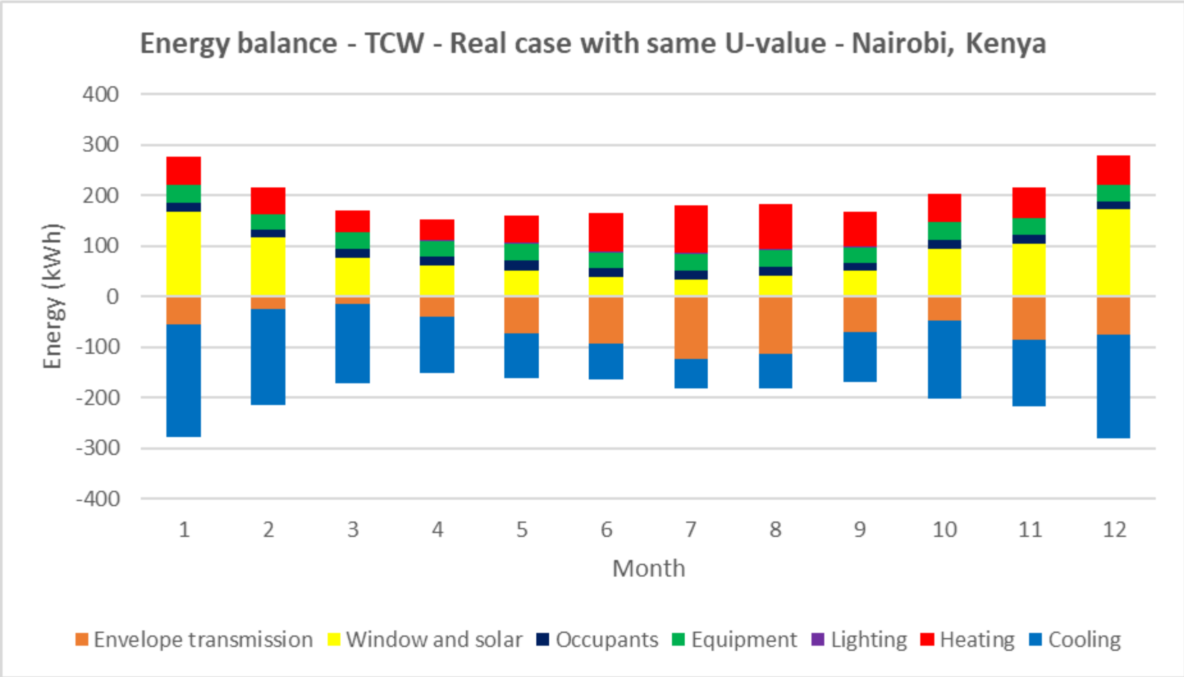

Fig.104. Energy balance - TCW - Real case with same U-value - Nairobi, Kenya. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 76. Energy balance - TCW - Real case with same U-value - Nairobi, Kenya. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - TCW - Real case with same U-value - Nairobi, Kenya (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-55	168	18	35	0	56	-223
2	-26	117	16	30	0	52	-190
3	-14	76	17	33	1	43	-157
4	-39	62	16	32	2	40	-113
5	-74	52	18	35	2	54	-88
6	-92	39	17	32	2	76	-73
7	-123	33	17	33	2	95	-58
8	-114	40	18	35	2	88	-69
9	-70	52	16	30	2	70	-100
10	-47	95	18	35	1	54	-156
11	-85	104	17	33	0	62	-133
12	-76	173	16	32	0	59	-205
Total	**-814**	**1011**	**204**	**392**	**15**	**749**	**-1564**
During heating (3728.9 h)	-729	-170	43	83	15	749	0
During cooling (3885.6 h)	46	1118	139	266	0	0	-1564
Rest of time	-131	63	22	42	0	0	0

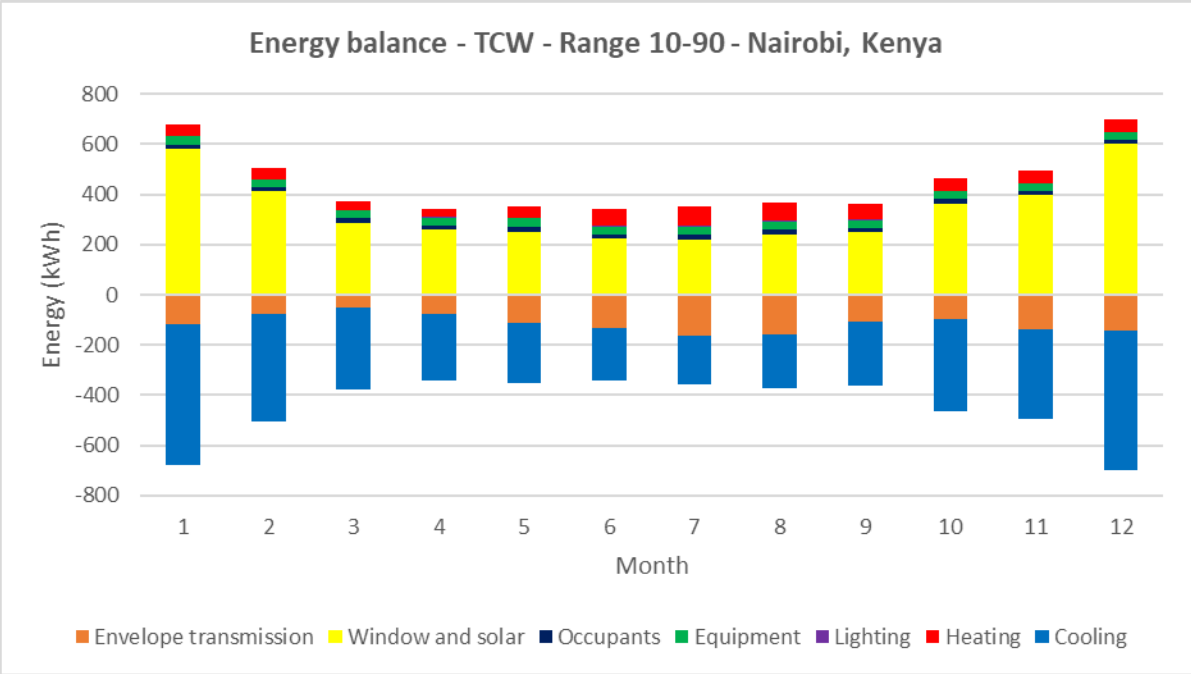

Fig.105. Energy balance - TCW - Range 10-90 - Nairobi, Kenya. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 77. Energy balance - TCW - Range 10-90 - Nairobi, Kenya. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - TCW - Range 10-90 - Nairobi, Kenya (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-119	580	18	35	0	46	-560
2	-75	414	16	30	0	45	-431
3	-52	287	17	33	0	37	-323
4	-77	260	16	32	1	33	-267
5	-114	253	18	35	1	46	-240
6	-132	224	16	32	1	67	-209
7	-164	222	17	33	1	81	-190
8	-156	240	18	35	1	76	-214
9	-109	252	16	30	1	62	-252
10	-94	363	18	35	1	46	-369
11	-138	396	17	33	0	50	-359
12	-144	602	16	32	0	47	-554
Total	**-1373**	**4091**	**203**	**392**	**8**	**634**	**-3968**
During heating (3219.6 h)	-701	-42	31	59	8	634	0
During cooling (4548.2 h)	-482	3992	157	303	0	0	-3967
Rest of time	-191	141	15	29	0	0	-1

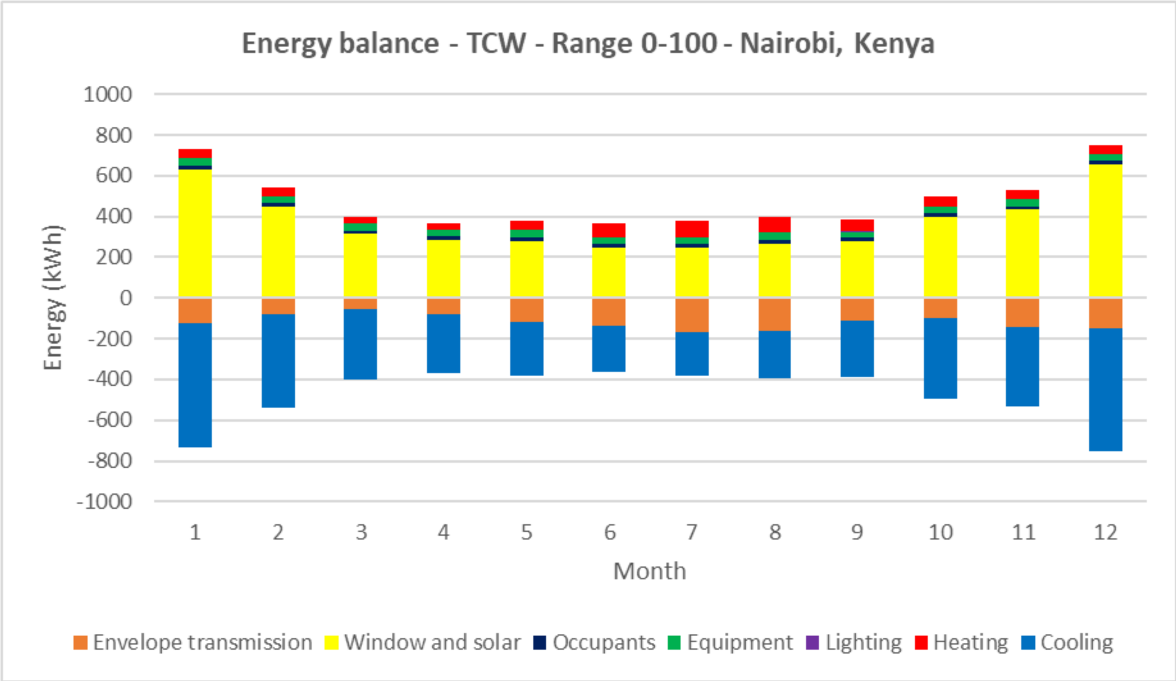

Fig.106. Energy balance - TCW - Range 0-100 - Nairobi, Kenya. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 78. Energy balance - TCW - Range 0-100 - Nairobi, Kenya. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - TCW - Range 0-100 - Nairobi, Kenya (kWh)							
Month	**Envelope transmission**	**Window and solar**	**Occupants**	**Equipment**	**Lighting**	**Heating**	**Cooling**
1	-126	632	18	35	0	45	-605
2	-80	450	16	30	0	45	-462
3	-57	313	17	33	0	37	-345
4	-81	286	16	32	1	33	-288
5	-119	280	18	35	1	45	-262
6	-136	249	16	32	1	66	-229
7	-170	248	17	33	1	79	-210
8	-161	268	18	35	1	76	-236
9	-113	279	16	30	1	61	-274
10	-101	397	18	35	1	46	-397
11	-143	434	17	33	0	49	-391
12	-151	657	16	32	0	46	-601
Total	**-1436**	**4494**	**203**	**392**	**8**	**625**	**-4299**
During heating (3166.2 h)	-696	-34	30	57	8	625	0
During cooling (4602 h)	-549	4383	159	307	0	0	-4300
Rest of time	-191	144	15	28	0	0	1

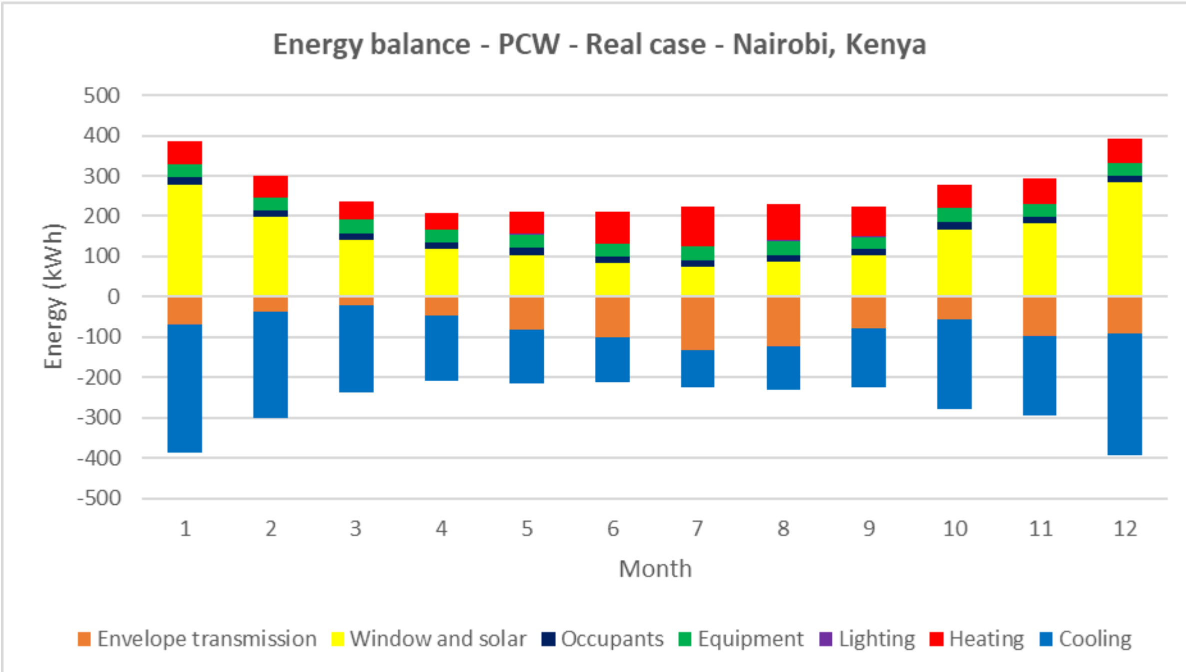

Fig.107. Energy balance - PCW - Real case - Nairobi, Kenya. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 79. Energy balance - PCW - Real case - Nairobi, Kenya. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - PCW - Real case - Nairobi, Kenya (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-68	278	18	35	0	57	-321
2	-36	199	16	30	0	55	-264
3	-23	141	17	33	1	45	-215
4	-47	117	16	32	1	42	-162
5	-82	103	18	35	2	56	-132
6	-100	83	16	32	2	79	-111
7	-131	75	17	33	2	97	-92
8	-122	86	18	35	2	90	-109
9	-79	103	16	30	1	73	-145
10	-57	168	18	35	1	56	-221
11	-96	181	17	33	0	63	-199
12	-91	283	16	32	0	61	-302
Total	**-933**	**1816**	**203**	**392**	**11**	**771**	**-2272**
During heating (3603.7 h)	-704	-199	38	73	11	771	0
During cooling (4114.8 h)	-104	1948	147	284	0	0	-2271
Rest of time	-125	67	18	35	0	0	0

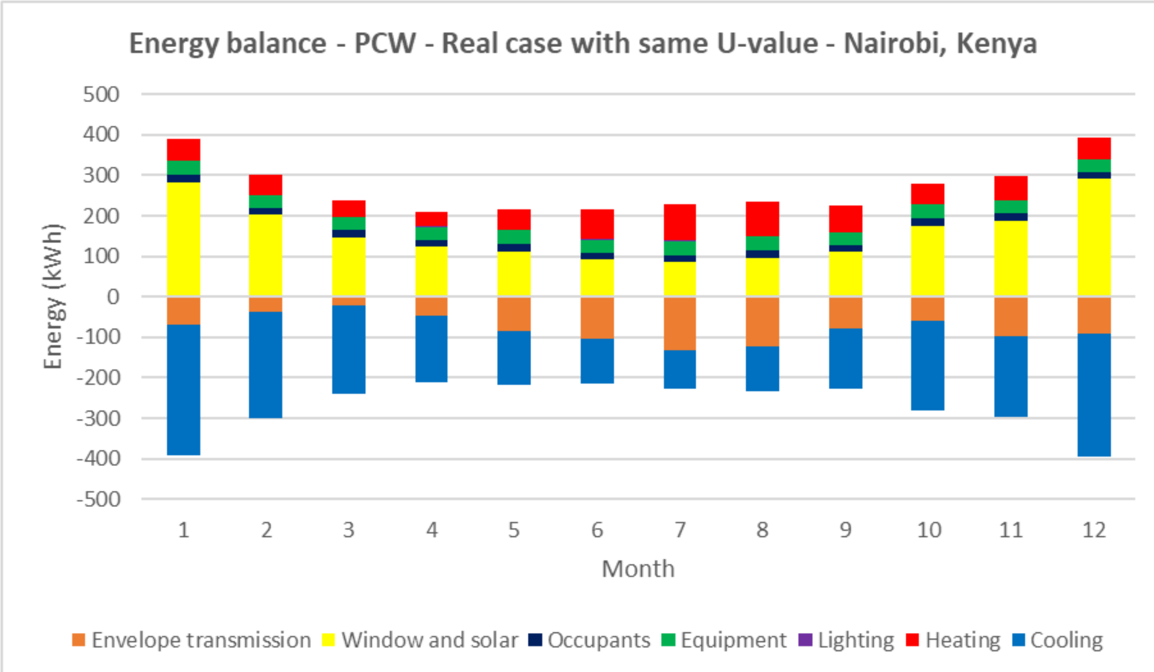

Fig.108. Energy balance - PCW - Real case with same U-value - Nairobi, Kenya. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 80. Energy balance - PCW - Real case with same U-value - Nairobi, Kenya. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - PCW - Real case with same U-value - Nairobi, Kenya (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-69	284	18	35	0	53	-321
2	-37	205	16	30	0	50	-264
3	-23	147	17	33	1	41	-216
4	-48	124	16	32	1	37	-164
5	-83	112	18	35	2	51	-135
6	-103	93	16	32	2	73	-113
7	-132	86	17	33	2	89	-95
8	-124	97	18	35	2	84	-111
9	-80	113	16	30	1	67	-147
10	-59	175	18	35	1	52	-222
11	-97	188	17	33	0	58	-201
12	-92	291	16	32	0	56	-304
Total	**-948**	**1913**	**203**	**392**	**12**	**711**	**-2294**
During heating (3537.1 h)	-698	-142	37	71	11	711	0
During cooling (4161.8 h)	-111	1975	148	284	0	0	-2294
Rest of time	-139	80	19	36	0	0	0

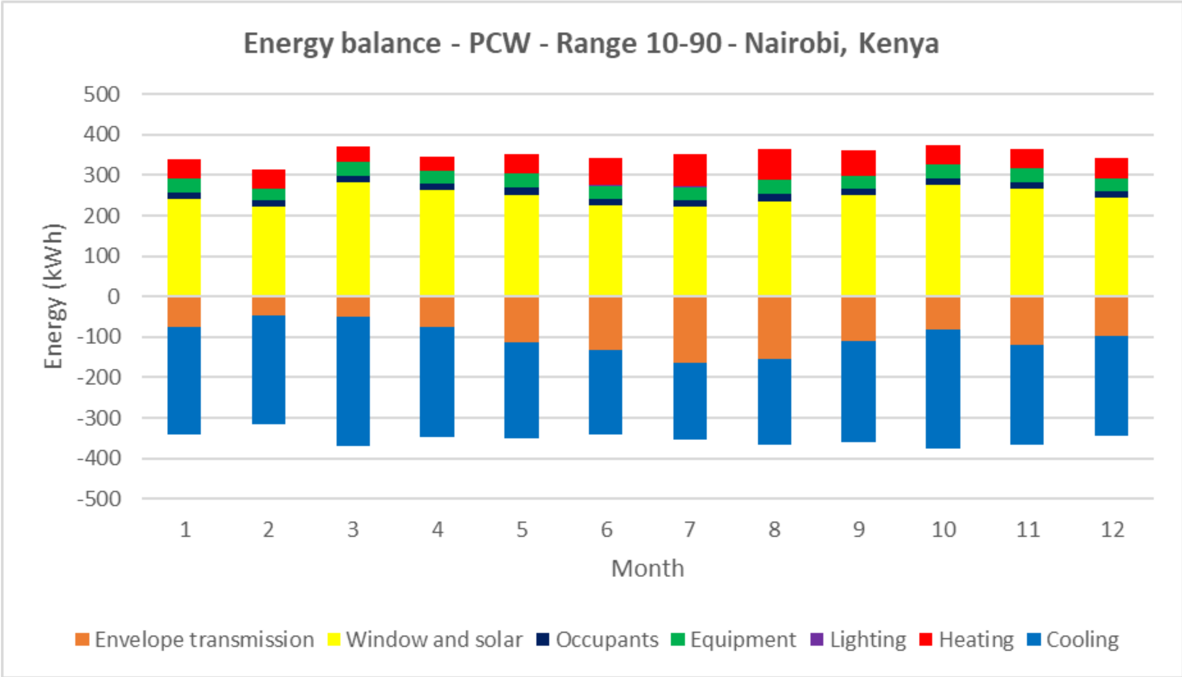

Fig.109. Energy balance - PCW - Range 10-90 - Nairobi, Kenya. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 81. Energy balance - PCW - Range 10-90 - Nairobi, Kenya. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - PCW - Range 10-90 - Nairobi, Kenya (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-75	240	18	35	0	48	-267
2	-47	222	16	30	0	46	-268
3	-51	282	17	33	0	37	-319
4	-77	263	16	32	1	33	-269
5	-114	251	18	35	1	46	-238
6	-132	226	16	32	1	66	-210
7	-165	221	17	33	1	80	-188
8	-155	236	18	35	1	76	-211
9	-109	252	16	30	1	62	-252
10	-83	274	18	35	1	47	-293
11	-119	266	17	33	0	50	-249
12	-97	245	16	32	0	50	-247
Total	**-1224**	**2979**	**203**	**392**	**8**	**639**	**-3009**
During heating (3240.2 h)	-707	-39	31	59	8	639	0
During cooling (4509.6 h)	-326	2878	157	303	0	0	-3008
Rest of time	-191	140	16	30	0	0	-1

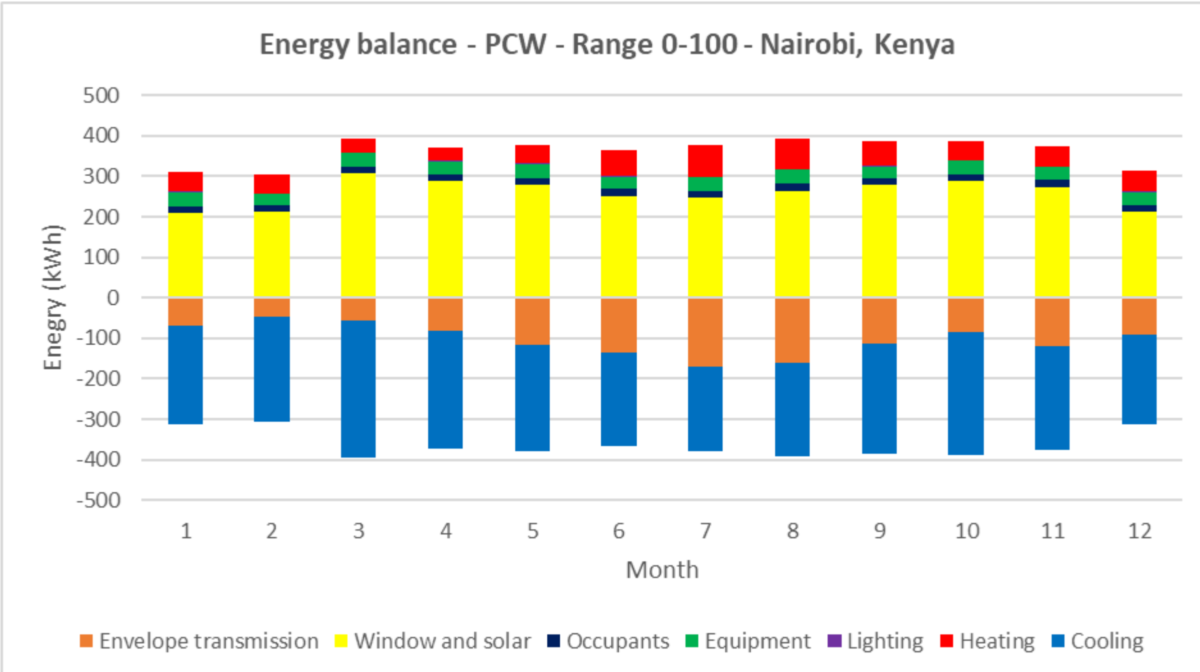

Fig.110. Energy balance - PCW - Range 0-100 - Nairobi, Kenya. Positive values represent heat flows in to the building and negative values represent heat flows out of the building.

Table 82. Energy balance - PCW - Range 0-100 - Nairobi, Kenya. Each category is presented per month and during heating, cooling and rest of time.

Energy balance - PCW - Range 0-100 - Nairobi, Kenya (kWh)

Month	Envelope transmission	Window and solar	Occupants	Equipment	Lighting	Heating	Cooling
1	-69	208	18	35	3	47	-243
2	-47	212	16	30	1	46	-259
3	-55	308	17	33	0	36	-340
4	-81	290	16	32	1	32	-291
5	-118	278	18	35	1	45	-260
6	-136	252	16	32	1	65	-231
7	-170	247	17	33	1	79	-208
8	-160	264	18	35	1	75	-233
9	-113	279	16	30	1	60	-273
10	-85	288	18	35	1	46	-303
11	-120	273	17	33	1	50	-254
12	-91	212	16	32	3	50	-223
Total	**-1245**	**3109**	**203**	**392**	**15**	**630**	**-3117**
During heating (3199.1 h)	-703	-31	30	57	8	630	0
During cooling (4559.6 h)	-356	3003	159	306	7	0	-3117
Rest of time	-185	137	15	29	0	0	0

A.4.7 Solar heat gain peak loads

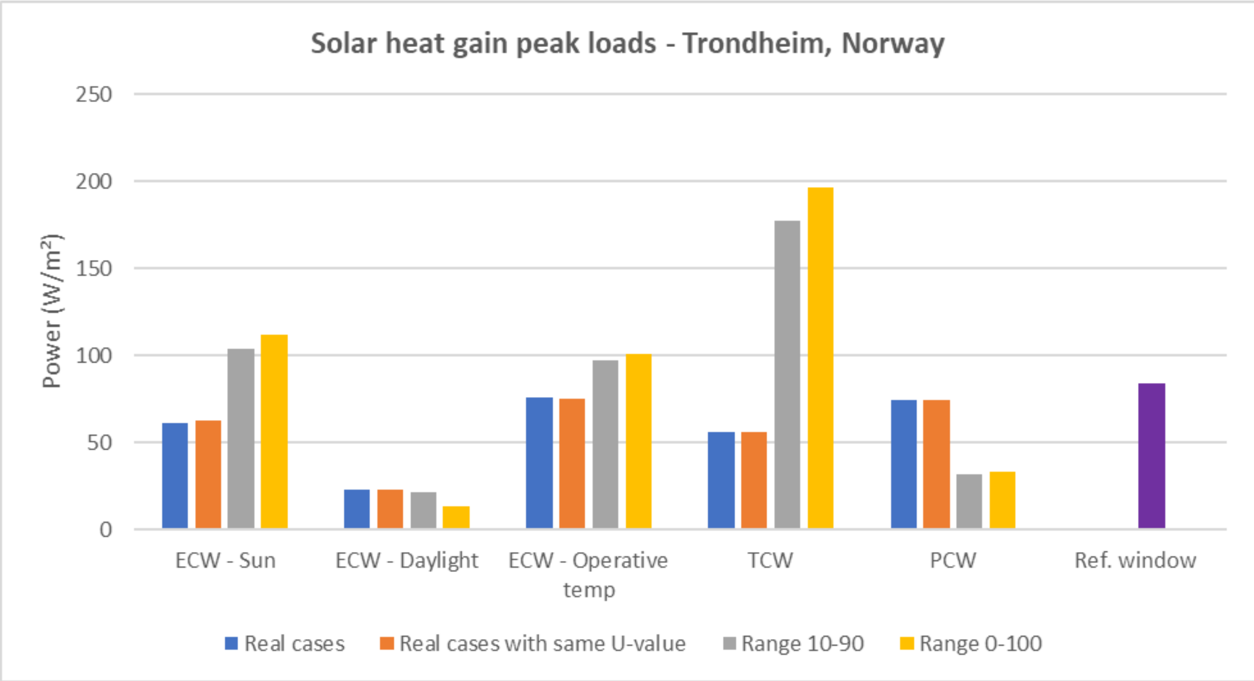

Fig.111. Solar heat gain peak loads for all cases in Trondheim, Norway. Each column represents the highest solar heat gain power during an entire year. Values are represented in W/m^2.

Table 83. Solar heat gain peak loads for all cases in Trondheim, Norway. Each column represents the highest solar heat gain power during an entire year. Values are represented in W/m^2.

Solar heat gain peak loads - Trondheim, Norway (W/m²)

Window technology	Real cases	Real cases with same U-value	Range 10-90	Range 0-100
ECW - Sun	61	63	104	112
ECW - Daylight	23	23	21	14
ECW - Operative temp	76	75	97	101
TCW	56	56	178	197
PCW	75	75	32	34
Ref. window	84	84	84	84

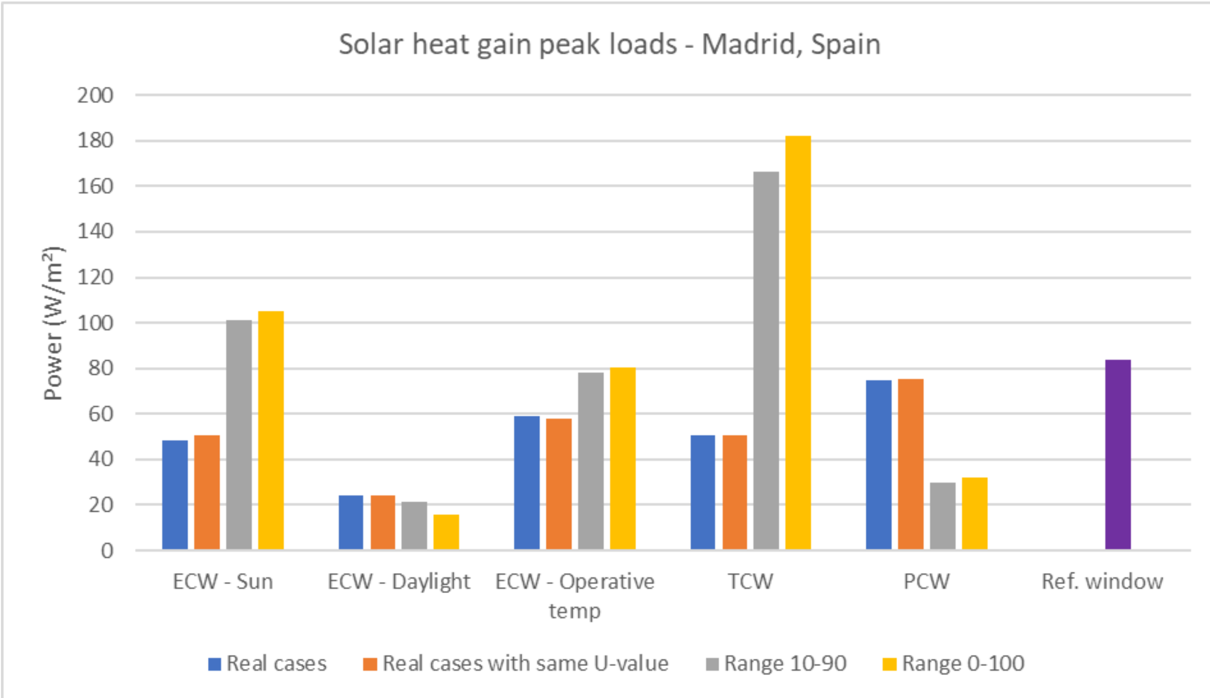

Fig.112. Solar heat gain peak loads for all cases in Madrid, Spain. Each column represents the highest solar heat gain power during an entire year. Values are represented in W/m^2.

Table 84. Solar heat gain peak loads for all cases in Madrid, Spain. Each column represents the highest solar heat gain power during an entire year. Values are represented in W/m^2.

Solar heat gain peak loads - Madrid, Spain (W/m²)

Window technology	Real cases	Real cases with same U-value	Range 10-90	Range 0-100
ECW - Sun	49	51	101	105
ECW - Daylight	24	24	21	16
ECW - Operative temp	59	58	78	80
TCW	51	51	166	182
PCW	75	75	30	32
Ref. window	84	84	84	84

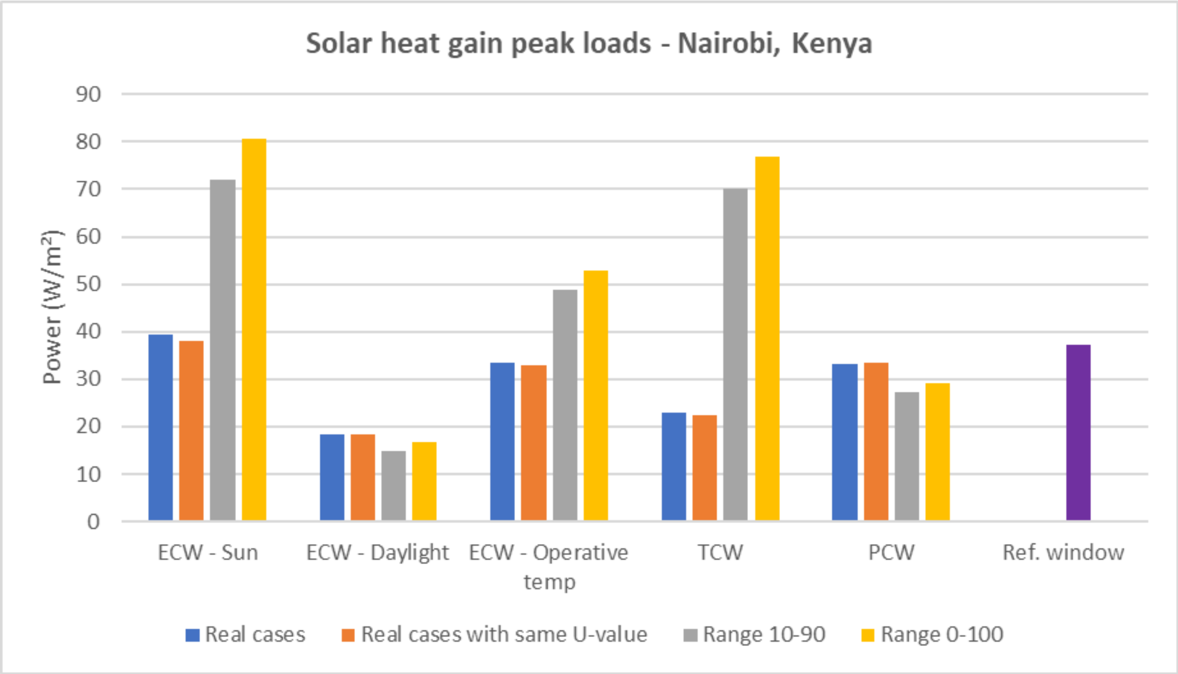

Fig.113. Solar heat gain peak loads for all cases in Nairobi, Kenya. Each column represents the highest solar heat gain power during an entire year. Values are represented in W/m²^2.

Table 85. Solar heat gain peak loads for all cases in Nairobi, Kenya. Each column represents the highest solar heat gain power during an entire year. Values are represented in W/m^2.

Solar heat gain peak loads - Nairobi, Kenya (W/m²)

Window technology	Real cases	Real cases with same U-value	Range 10-90	Range 0-100
ECW - Sun	39	38	72	81
ECW - Daylight	18	18	15	17
ECW - Operative temp	34	33	49	53
TCW	23	22	70	77
PCW	33	33	27	29
Ref. window	37	37	37	37

A.4.8 Heating peak loads

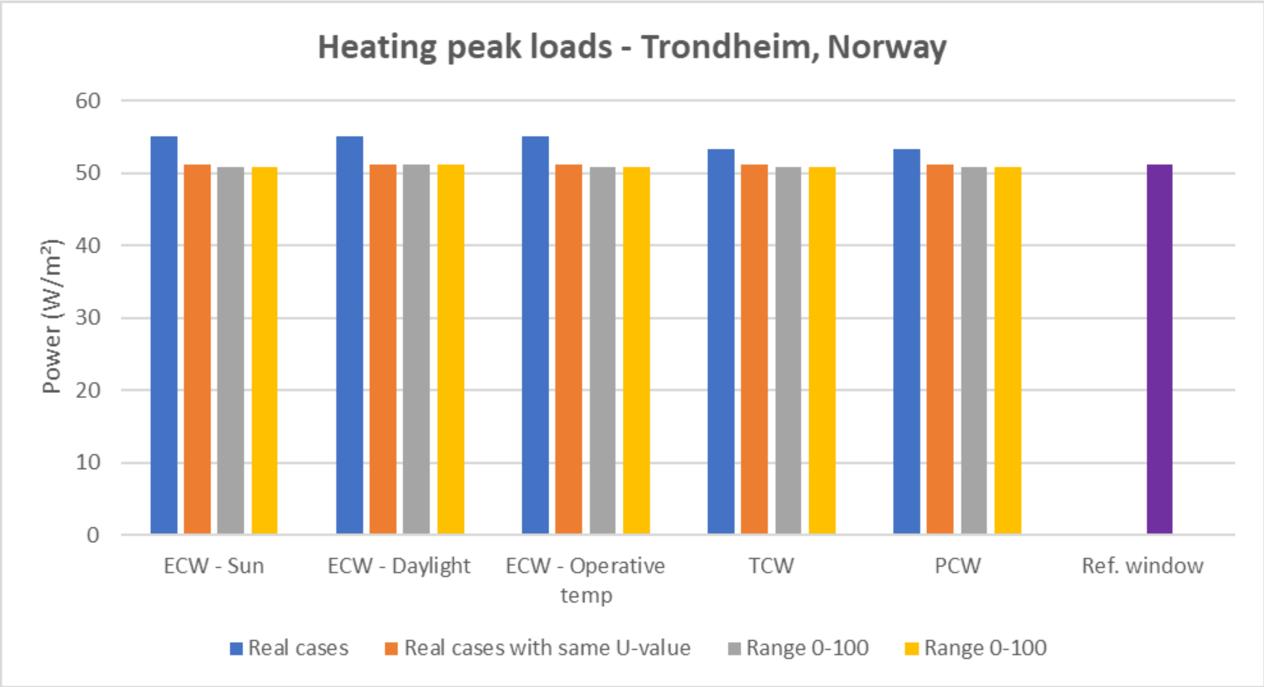

Fig.114. Heating peak loads for all cases in Trondheim, Norway. Each column represents the highest heating power during an entire year. Values are represented in W/m^2.

Table 86. Heating peak loads for all cases in Trondheim, Norway. Each column represents the highest heating power during an entire year. Values are represented in W/m^2.

Window technology	Real cases	Real cases with same U-value	Range 0-100	Range 0-100
ECW - Sun	55	51	51	51
ECW - Daylight	55	51	51	51
ECW - Operative temp	55	51	51	51
TCW	53	51	51	51
PCW	53	51	51	51
Ref. window	51	51	51	51

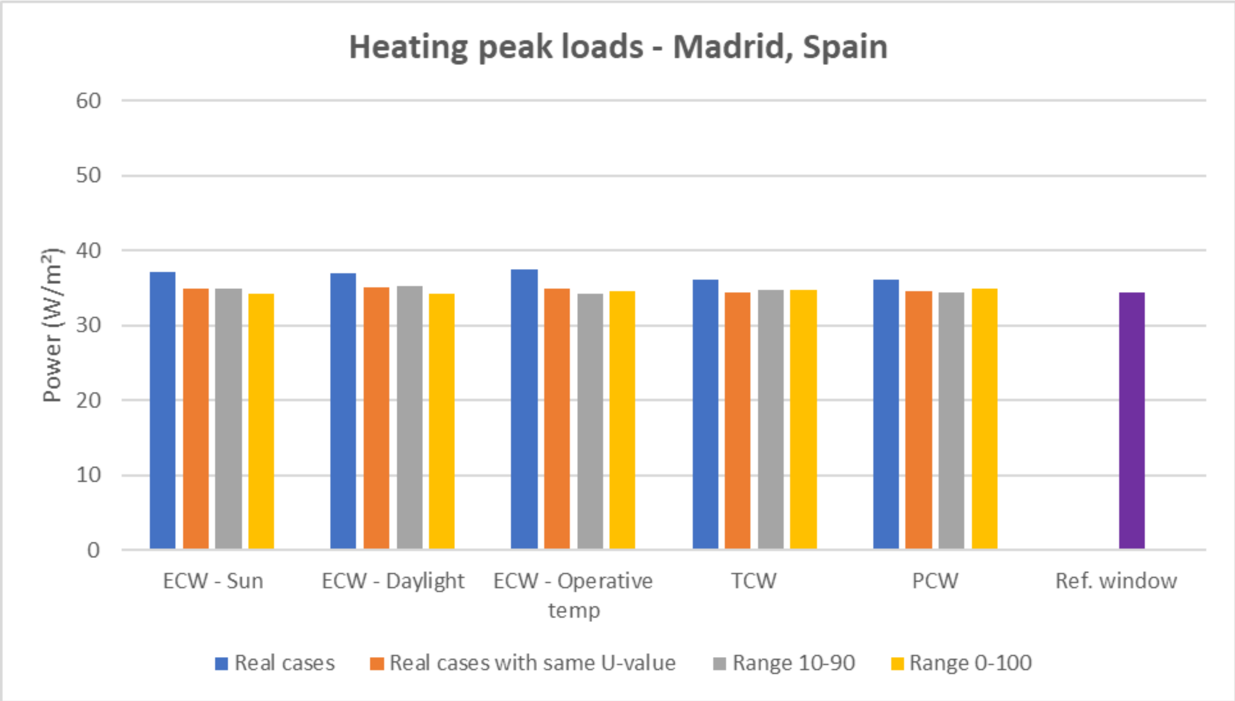

Fig.115. Heating peak loads for all cases in Madrid, Spain. Each column represents the highest heating power during an entire year. Values are represented in W/m^2.

Table 87. Heating peak loads for all cases in Madrid, Spain. Each column represents the highest heating power during an entire year. Values are represented in W/m^2.

Heating peak loads - Madrid, Spain (W/m²)

Window technology	Real cases	Real cases with same U-value	Range 10-90	Range 0-100
ECW - Sun	37	35	35	34
ECW - Daylight	37	35	35	34
ECW - Operative temp	37	35	34	35
TCW	36	34	35	35
PCW	36	35	34	35
Ref. window	34	34	34	34

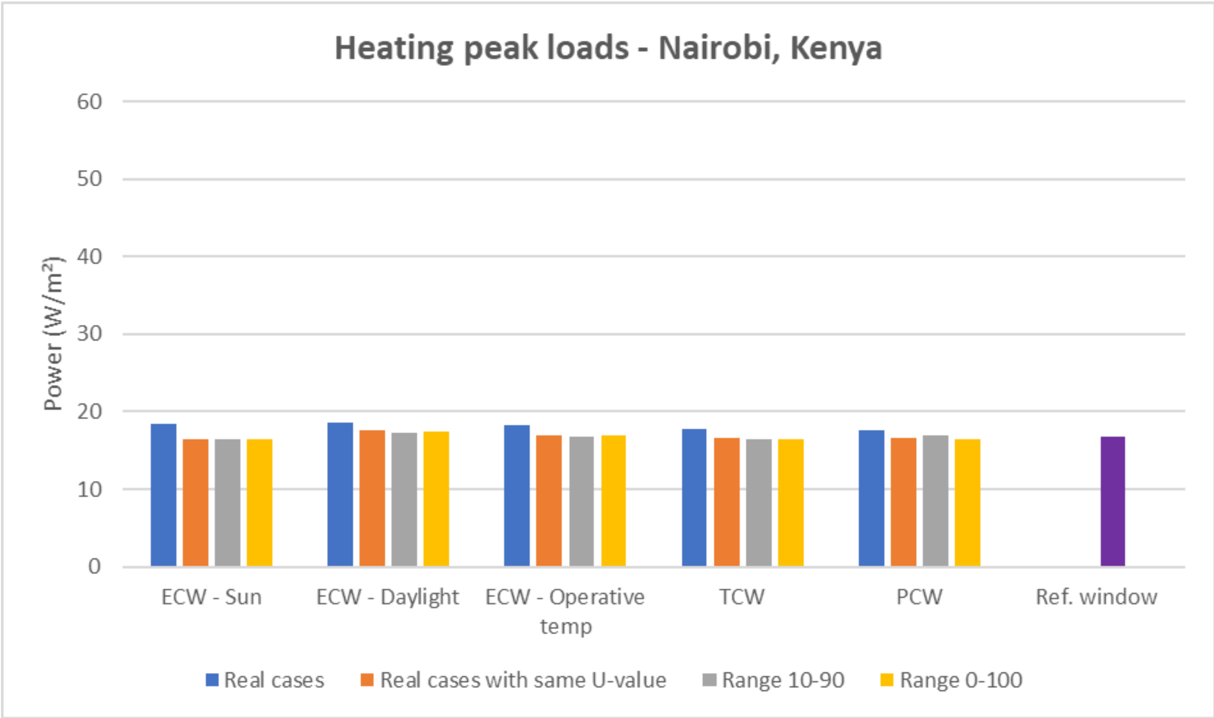

Fig.116. Heating peak loads for all cases in Nairobi, Kenya. Each column represents the highest heating power during an entire year. Values are represented in W/m^2.

Table 88. Heating peak loads for all cases in Nairobi, Kenya. Each column represents the highest heating power during an entire year. Values are represented in W/m^2.

Heating peak loads - Nairobi, Kenya (W/m²)

Window technology	Real cases	Real cases with same U-value	Range 10-90	Range 0-100
ECW - Sun	18	16	16	16
ECW - Daylight	19	18	17	18
ECW - Operative temp	18	17	17	17
TCW	18	17	17	16
PCW	18	17	17	16
Ref. window	17	17	17	17

A.4.9 Cooling peak loads

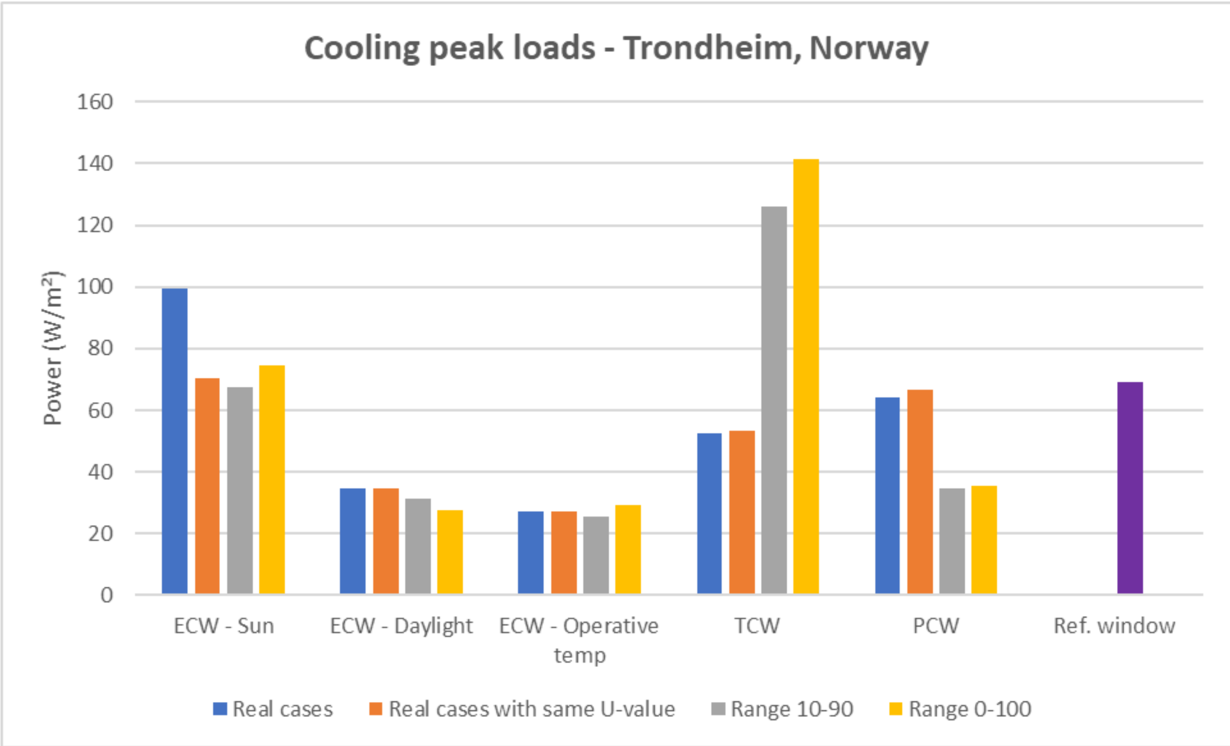

Fig.117. Cooling peak loads for all cases in Trondheim, Norway. Each column represents the highest cooling power during an entire year. Values are represented in W/m^2.

Table 89. Cooling peak loads for all cases in Trondheim, Norway. Each column represents the highest cooling power during an entire year. Values are represented in W/m^2.

Cooling peak loads - Trondheim, Norway (W/m²)

Window technology	Real cases	Real cases with same U-value	Range 10-90	Range 0-100
ECW - Sun	100	70	67	75
ECW - Daylight	35	35	31	28
ECW - Operative temp	27	27	25	29
TCW	53	53	126	142
PCW	64	67	35	36
Ref. window	69	69	69	69

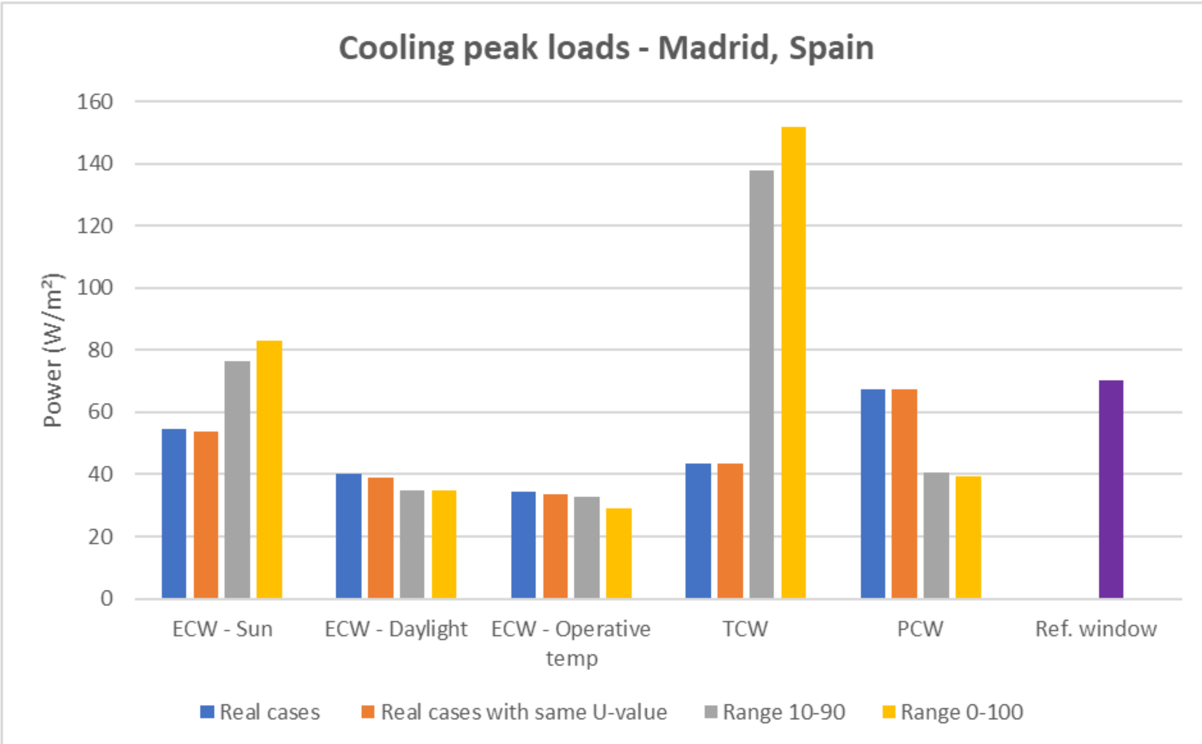

Fig.118. Cooling peak loads for all cases in Madrid, Spain. Each column represents the highest cooling power during an entire year. Values are represented in W/m^2.

Table 90. Cooling peak loads for all cases in Madrid, Spain. Each column represents the highest cooling power during an entire year. Values are represented in W/m^2.

Cooling peak loads - Madrid, Spain (W/m^2)

Window technology	Real cases	Real cases with same U-value	Range 10-90	Range 0-100
ECW - Sun	55	54	76	83
ECW - Daylight	40	39	35	35
ECW - Operative temp	34	33	33	29
TCW	43	43	138	152
PCW	68	67	41	39
Ref. window	70	70	70	70

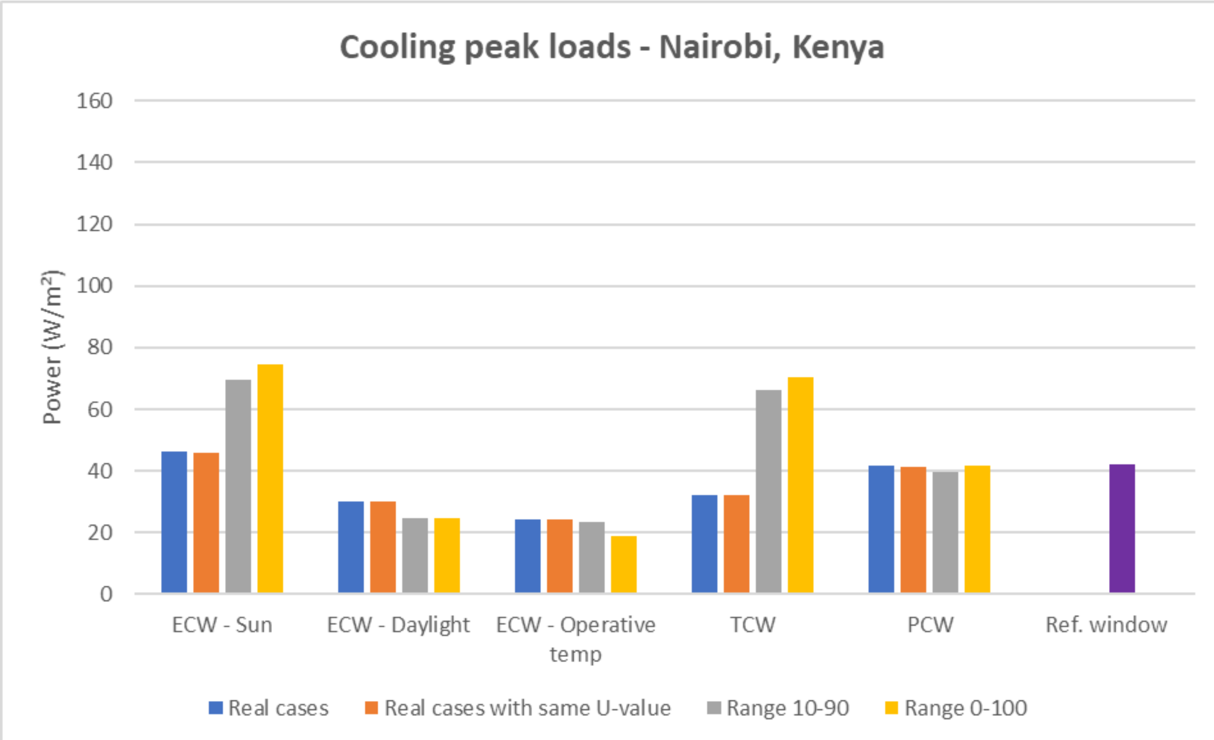

Fig.119. Cooling peak loads for all cases in Nairobi, Kenya. Each column represents the highest cooling power during an entire year. Values are represented in W/m^2.

Table 91. Cooling peak loads for all cases in Nairobi, Kenya. Each column represents the highest cooling power during an entire year. Values are represented in W/m^2.

Cooling peak loads - Nairobi, Kenya (W/m²)

Window technology	Real cases	Real cases with same U-value	Range 10-90	Range 0-100
ECW - Sun	46	46	69	75
ECW - Daylight	30	30	25	25
ECW - Operative temp	24	24	23	19
TCW	32	32	66	70
PCW	42	41	40	42
Ref. window	42	42	42	42

A.4.10 Sensitivity analysis - TCW, PCW and ECW – Sun (Range 0-100)

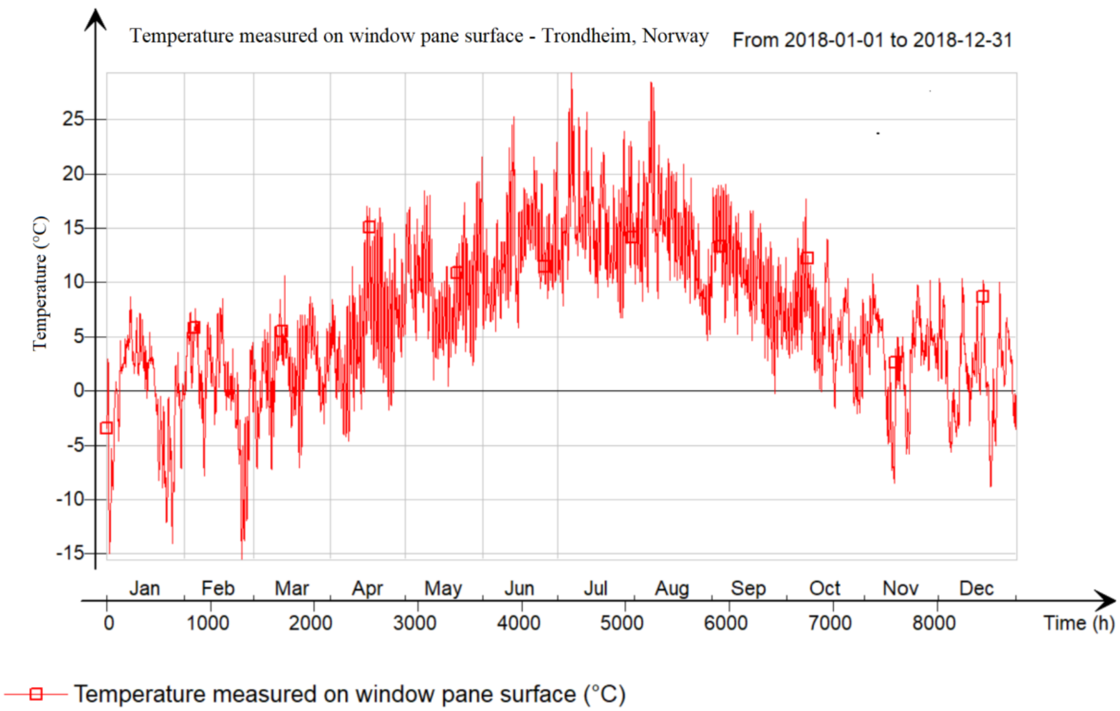

Fig.120. Temperature measured on window pane as a function of time for Trondheim, Norway.

Table 92. Sensitivity analysis for TCW – Range 0-100 – Trondheim, Norway. The table shows the impact on delivered energy for different control levels of temperature divided into heating, cooling, equipment and lighting.

TCW - Range 0-100 - Trondheim, Norway

Window technology	Control levels (°C)	Heating	%	Cooling	%	Equipment	%	Lightning	%	Total	%
TCW	10 - 65	4559	86%	4165	342%	392	100%	22	90%	9138	132%
TCW	10 - 55	4559	86%	4098	337%	392	100%	22	90%	9070	131%
TCW	10 - 45	4562	86%	3973	326%	392	100%	22	90%	8948	129%
TCW	10 - 35	4567	86%	3700	304%	392	100%	22	90%	8681	125%
TCW	10 - 25	4586	87%	3013	248%	392	100%	24	99%	8014	116%
TCW	10 - 15	4751	90%	1722	141%	392	100%	50	210%	6915	100%
TCW	0 - 15	5145	97%	707	58%	392	100%	62	257%	6305	91%
TCW	-10 - 15	5662	107%	272	22%	392	100%	76	316%	6401	92%
Ref. window	N/A	5290	100%	1217	100%	392	100%	24	100%	6922	100%

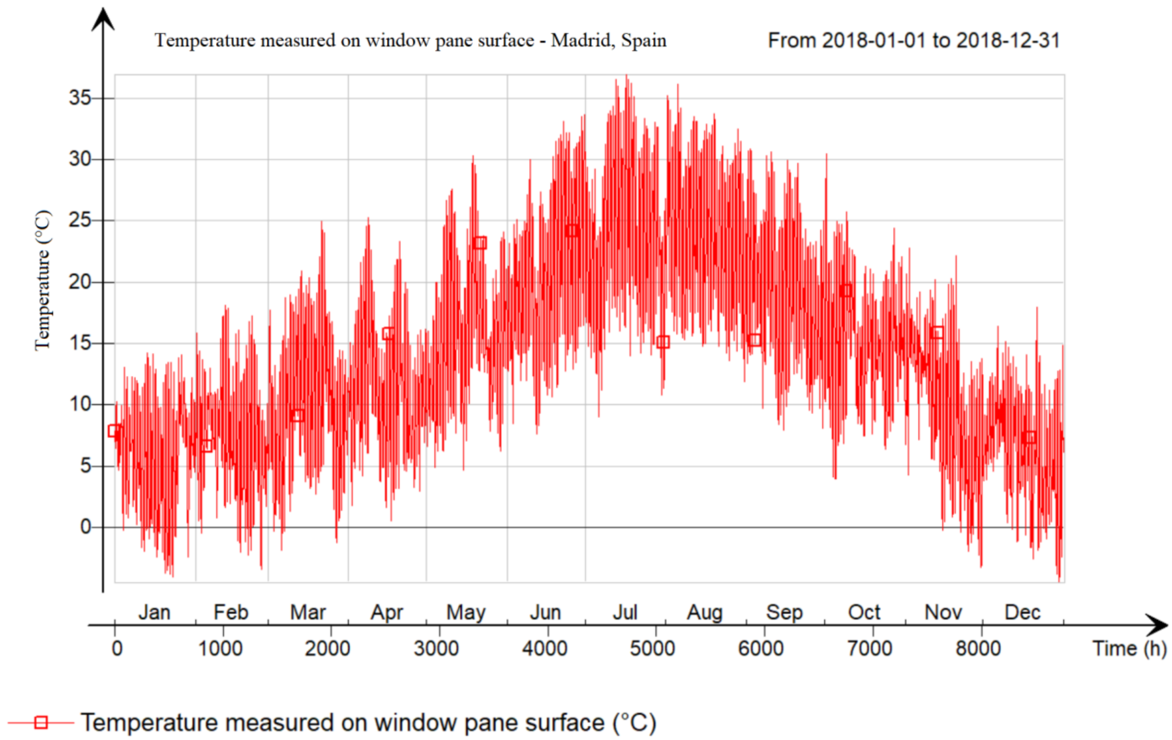

Fig.121. Temperature measured on window pane surface as a function of time for Madrid, Spain.

Table 93. Sensitivity analysis for TCW – Range 0-100 – Madrid, Spain. The table shows the impact on delivered energy for different control levels of temperature divided into heating, cooling, equipment and lighting.

TCW - Range 0-100 - Madrid, Spain

Window technology	Control levels (°C)	Heating	%	Cooling	%	Equipment	%	Lightning	%	Total	%
TCW	10 - 65	2041	88%	7739	228%	392	100%	14	81%	10186	166%
TCW	10 - 55	2045	88%	7401	218%	392	100%	14	81%	9851	161%
TCW	10 - 45	2050	89%	6806	200%	392	100%	14	82%	9261	151%
TCW	10 - 35	2064	89%	5746	169%	392	100%	19	112%	8221	134%
TCW	10 - 25	2106	91%	4191	123%	392	100%	42	247%	6731	110%
TCW	10 - 15	2278	98%	2388	70%	392	100%	81	474%	5138	84%
TCW	0 - 15	2558	111%	1018	30%	392	100%	90	531%	4058	66%
TCW	-10 - 15	2806	121%	723	21%	392	100%	101	591%	4021	66%
Ref. window	N/A	2313	100%	3401	100%	392	100%	17	100%	6123	100%

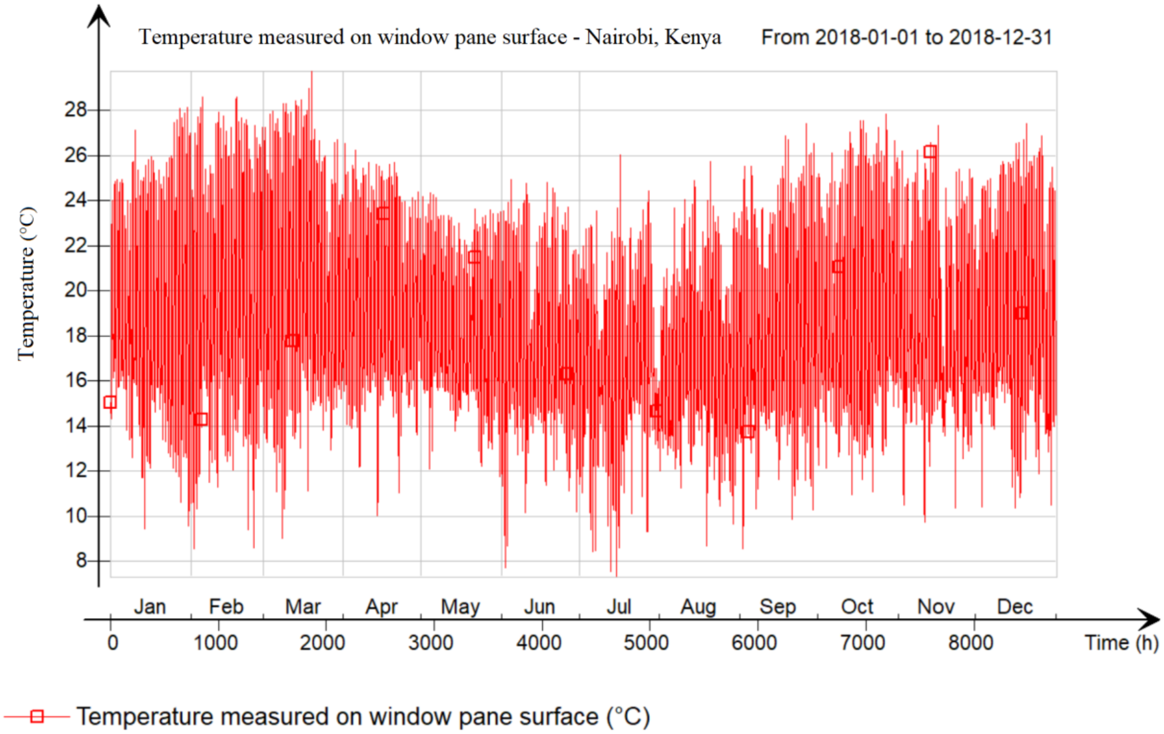

Fig.122. Temperature measured on window pane surface as a function of time for Nairobi, Kenya.

Table 94. Sensitivity analysis for TCW – Range 0-100 – Nairobi, Kenya. The table shows the impact on delivered energy for different control levels of temperature divided into heating, cooling, equipment and lighting.

TCW - Range 0-100 - Nairobi, Kenya

Window technology	Control levels (°C)	Heating	%	Cooling	%	Equipment	%	Lightning	%	Total	%
TCW	10 - 65	625	88%	4374	189%	392	100%	8	84%	5399	158%
TCW	10 - 55	629	89%	4124	178%	392	100%	8	85%	5152	151%
TCW	10 - 45	639	90%	3661	158%	392	100%	8	85%	4699	137%
TCW	10 - 35	622	88%	2726	118%	392	100%	8	90%	3748	110%
TCW	10 - 25	727	103%	1143	49%	392	100%	63	705%	2325	68%
TCW	10 - 15	857	121%	650	28%	392	100%	129	1432%	2027	59%
TCW	0 - 15	879	124%	641	28%	392	100%	131	1450%	2042	60%
TCW	-10 - 15	883	125%	639	28%	392	100%	131	1450%	2044	60%
Ref. window	N/A	708	100%	2311	100%	392	100%	9	100%	3420	100%

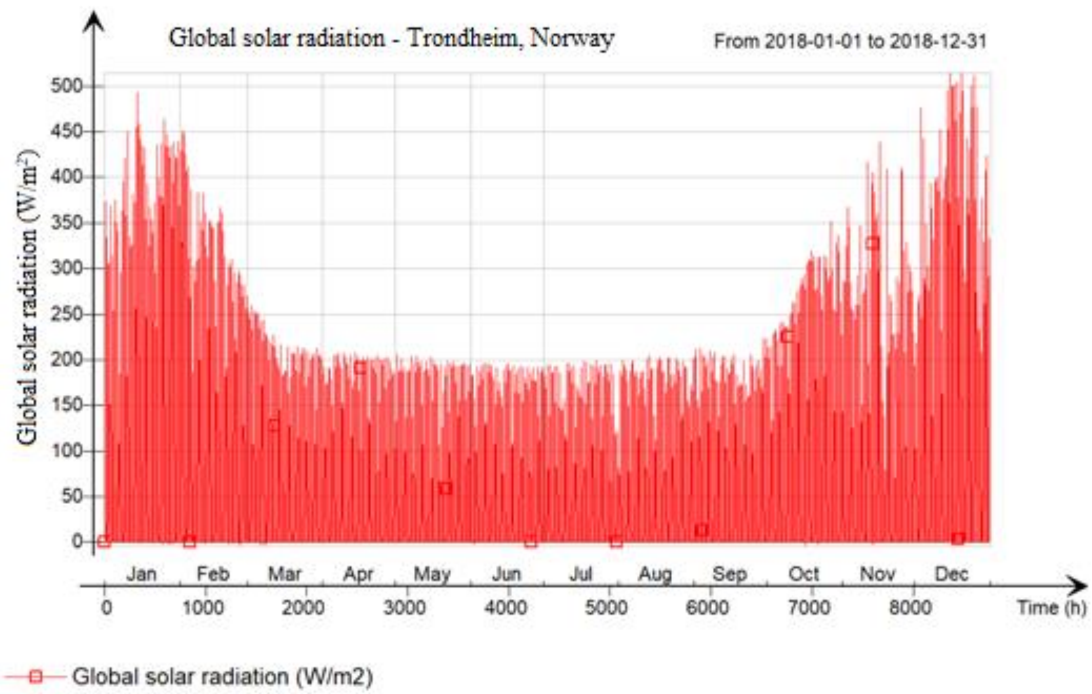

Fig.123. Global solar radiation as a function of time for Trondheim, Norway.

Table 95. Sensitivity analysis for PCW – Range 0-100 – Trondheim, Norway. The table shows the impact on delivered energy for different control levels of global solar radiation divided into heating, cooling, equipment and lighting.

PCW - Range 0-100 - Trondheim, Norway

Window technology	Control levels (W/m²)	Heating	%	Cooling	%	Equipment	%	Lightning	%	Total	%
PCW	100 - 800	4689	89%	1802	148%	392	100%	23	95%	6906	100%
PCW	100 - 700	4759	90%	1411	116%	392	100%	27	111%	6588	95%
PCW	100 - 600	4876	92%	1032	85%	392	100%	34	143%	6333	91%
PCW	100 - 500	5031	95%	680	56%	392	100%	44	183%	6146	89%
PCW	100 - 450	5125	97%	530	44%	392	100%	49	202%	6095	88%
PCW	100 - 400	5256	99%	398	33%	392	100%	54	227%	6100	88%
PCW	100 - 300	5594	106%	201	17%	392	100%	70	294%	6257	90%
PCW	100 - 200	6001	113%	122	10%	392	100%	92	384%	6607	95%
PCW	50 - 200	6168	117%	106	9%	392	100%	95	396%	6761	98%
PCW	50 - 100	6498	123%	86	7%	392	100%	117	488%	7093	102%
Ref. window	N/A	5290	100%	1217	100%	392	100%	24	100%	6923	100%

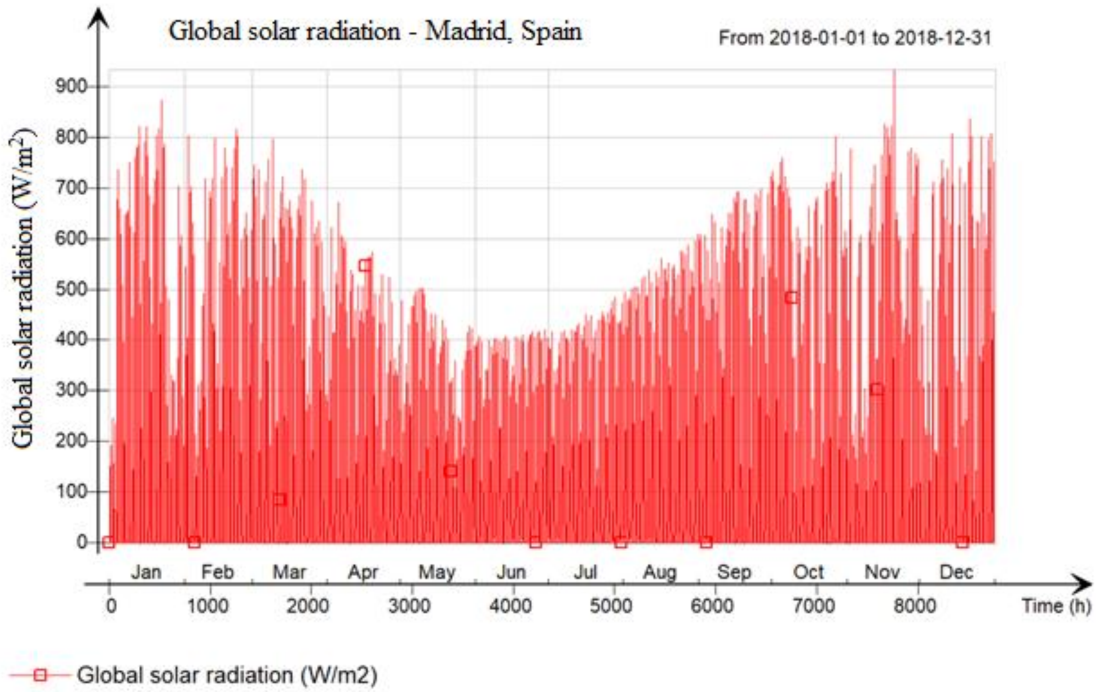

Fig.124. Global solar radiation as a function of time for Madrid, Spain.

Table 96. Sensitivity analysis for PCW – Range 0-100 – Madrid, Spain. The table shows the impact on delivered energy for different control levels of global solar radiation divided into heating, cooling, equipment and lighting.

PCW - Range 0-100 - Madrid, Spain

Window technology	Control levels (W/m²)	Heating	%	Cooling	%	Equipment	%	Lightning	%	Total	%
PCW	100 - 800	2131	92%	3841	113%	392	100%	18	109%	6381	104%
PCW	100 - 700	2176	94%	3166	93%	392	100%	26	160%	5759	94%
PCW	100 - 600	2258	98%	2521	74%	392	100%	38	229%	5208	85%
PCW	100 - 500	2389	103%	1930	57%	392	100%	54	326%	4764	78%
PCW	100 - 450	2469	107%	1675	49%	392	100%	63	382%	4599	75%
PCW	100 - 400	2562	111%	1456	43%	392	100%	72	435%	4481	73%
PCW	100 - 300	2782	120%	1145	34%	392	100%	89	541%	4408	72%
PCW	100 - 200	2958	128%	965	28%	392	100%	103	626%	4418	72%
PCW	50 - 200	3027	131%	891	26%	392	100%	105	636%	4414	72%
PCW	50 - 100	3171	137%	764	22%	392	100%	120	724%	4446	73%
Ref. window	N/A	2313	100%	3401	100%	392	100%	17	100%	6122	100%

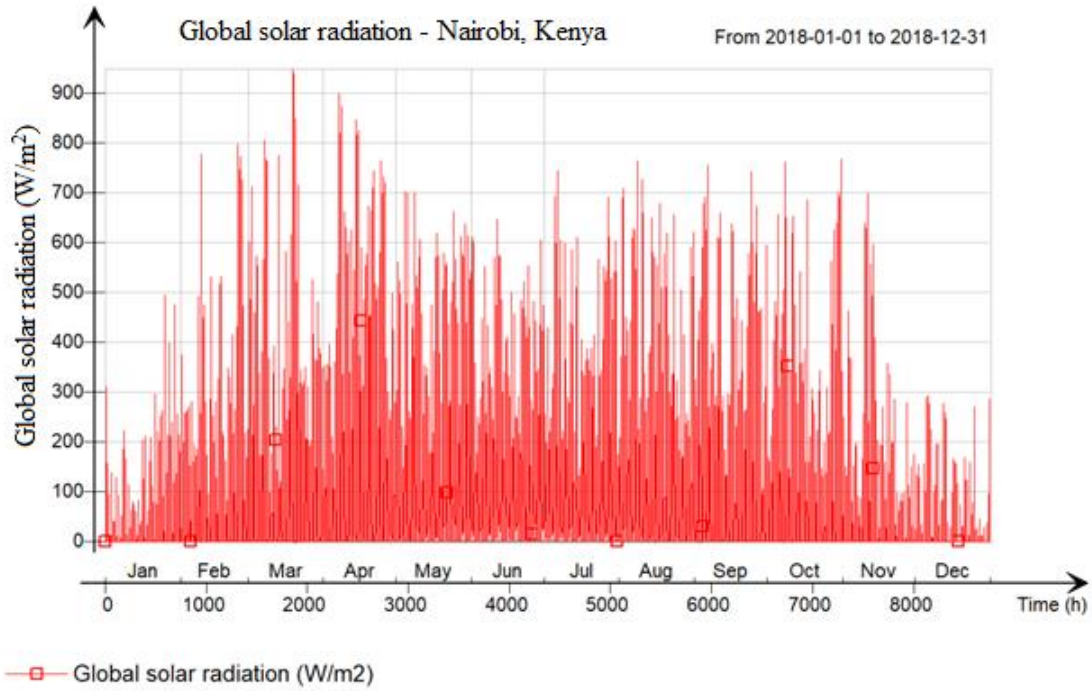

Fig.125. Global solar radiation as a function of time for Nairobi, Kenya.

Table 97. Sensitivity analysis for PCW – Range 0-100 – Nairobi, Kenya. The table shows the impact on delivered energy for different control levels of global solar radiation divided into heating, cooling, equipment and lighting.

PCW - Range 0-100 - Nairobi, Kenya

Window technology	Control levels (W/m²)	Heating	%	Cooling	%	Equipment	%	Lightning	%	Total	%
PCW	100 - 800	616	87%	4298	186%	392	100%	8	81%	5313	155%
PCW	100 - 700	617	87%	4108	178%	392	100%	7	81%	5124	150%
PCW	100 - 600	621	88%	3826	166%	392	100%	8	82%	4846	142%
PCW	100 - 500	627	89%	3432	148%	392	100%	11	116%	4461	130%
PCW	100 - 450	630	89%	3192	138%	392	100%	15	162%	4229	124%
PCW	100 - 400	635	90%	2916	126%	392	100%	20	211%	3962	116%
PCW	100 - 300	651	92%	2227	96%	392	100%	36	385%	3306	97%
PCW	100 - 200	682	96%	1274	55%	392	100%	77	833%	2425	71%
PCW	50 - 200	698	99%	1016	44%	392	100%	87	937%	2192	64%
PCW	50 - 100	774	109%	707	31%	392	100%	117	1266%	1990	58%
Ref. window	N/A	708	100%	2311	100%	392	100%	9	100%	3419	100%

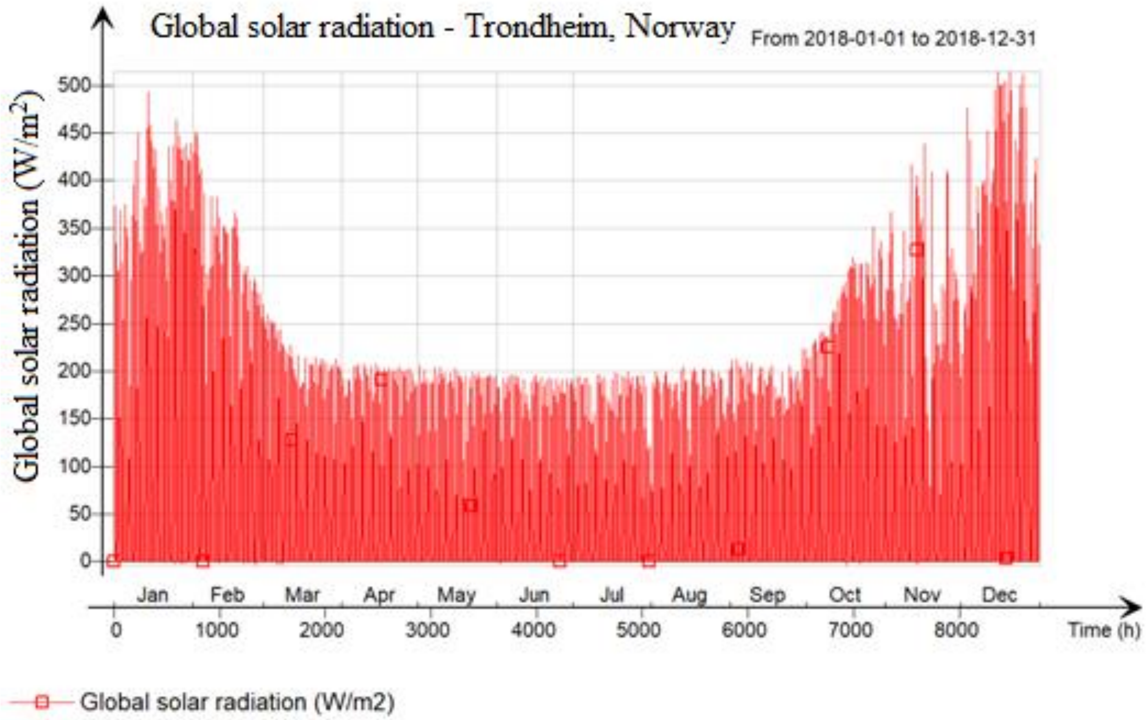

Fig.126. Global solar radiation as a function of time for Trondheim, Norway.

Table 98. Sensitivity analysis for ECW – Sun – Range 0-100 – Trondheim, Norway. The table shows the impact on delivered energy for different global radiation thresholds divided into heating, cooling, equipment and lighting.

ECW - Sun - Range 0-100 - Trondheim, Norway

Window technology	Global radiation (W/m²)	Heating	%	Cooling	%	Equipment	%	Lightning	%	Total	%
ECW Sun	50	6405	121%	97	8%	392	100%	116	481%	7009	101%
ECW Sun	100	6218	118%	106	9%	392	100%	108	449%	6823	99%
ECW Sun	200	5624	106%	198	16%	392	100%	87	362%	6300	91%
ECW Sun	300	5086	96%	753	62%	392	100%	65	270%	6295	91%
ECW Sun	400	4851	92%	1481	122%	392	100%	51	211%	6774	98%
ECW Sun	450	4763	90%	1890	155%	392	100%	45	186%	7089	102%
ECW Sun	500	4696	89%	2368	195%	392	100%	39	162%	7494	108%
ECW Sun	600	4610	87%	3321	273%	392	100%	29	122%	8352	121%
ECW Sun	700	4572	86%	3976	327%	392	100%	23	98%	8963	129%
ECW Sun	800	4565	86%	4241	348%	392	100%	22	91%	9219	133%
ECW Sun	900	4564	86%	4311	354%	392	100%	22	90%	9288	134%
ECW Sun	1000	4564	86%	4318	355%	392	100%	22	90%	9295	134%
Ref. window	N/A	5290	100%	1217	100%	392	100%	24	100%	6922	100%

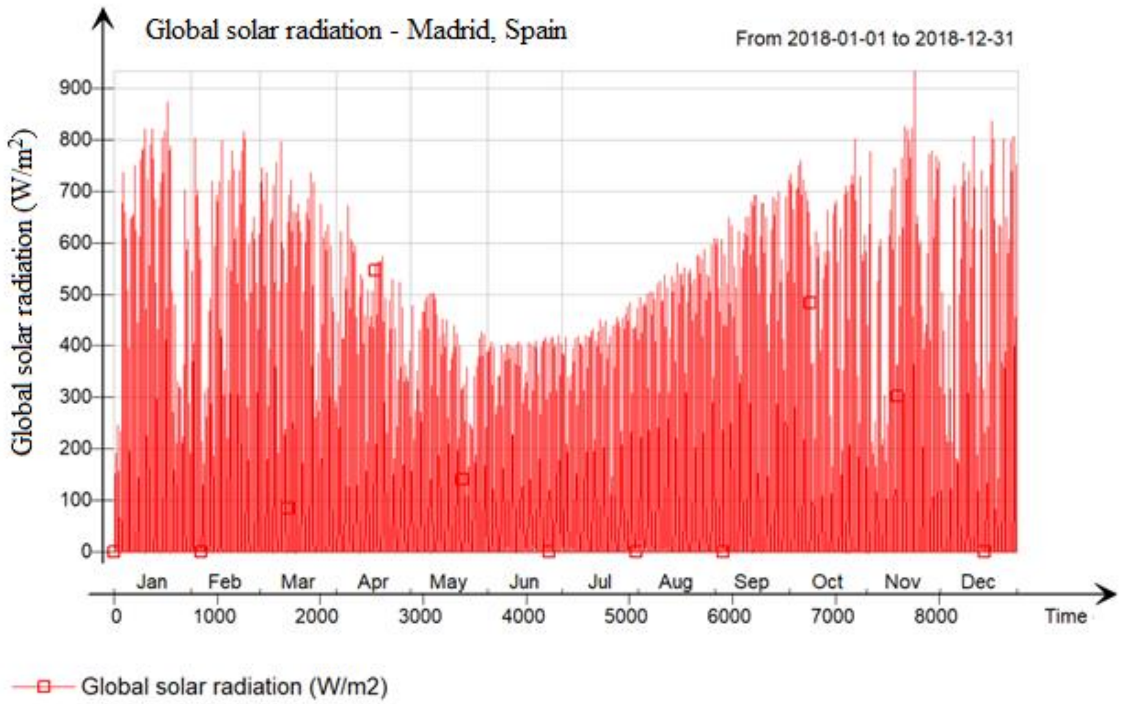

Fig.127. Global solar radiation as a function of time for Madrid, Spain.

Table 99. Sensitivity analysis for ECW – Sun – Range 0-100 – Madrid, Spain. The table shows the impact on delivered energy for different global radiation thresholds divided into heating, cooling, equipment and lighting.

ECW - Sun - Range 0-100 - Madrid, Spain

Window technology	Global radiation (W/m²)	Heating	%	Cooling	%	Equipment	%	Lightning	%	Total	%
ECW Sun	50	3094	134%	881	26%	392	100%	113	683%	4479	73%
ECW Sun	100	3036	131%	901	27%	392	100%	110	665%	4439	72%
ECW Sun	200	2793	121%	1116	33%	392	100%	97	585%	4398	72%
ECW Sun	300	2502	108%	1737	51%	392	100%	83	500%	4713	77%
ECW Sun	400	2285	99%	3009	88%	392	100%	64	389%	5750	94%
ECW Sun	450	2227	96%	3804	112%	392	100%	54	325%	6477	106%
ECW Sun	500	2160	93%	4636	136%	392	100%	45	272%	7232	118%
ECW Sun	600	2088	90%	6067	178%	392	100%	32	193%	8578	140%
ECW Sun	700	2051	89%	7586	223%	392	100%	20	118%	10048	164%
ECW Sun	800	2037	88%	8419	248%	392	100%	14	87%	10862	177%
ECW Sun	900	2035	88%	8510	250%	392	100%	14	84%	10951	179%
ECW Sun	1000	2035	88%	8520	251%	392	100%	14	84%	10961	179%
Ref. window	N/A	2313	100%	3401	100%	392	100%	17	100%	6122	100%

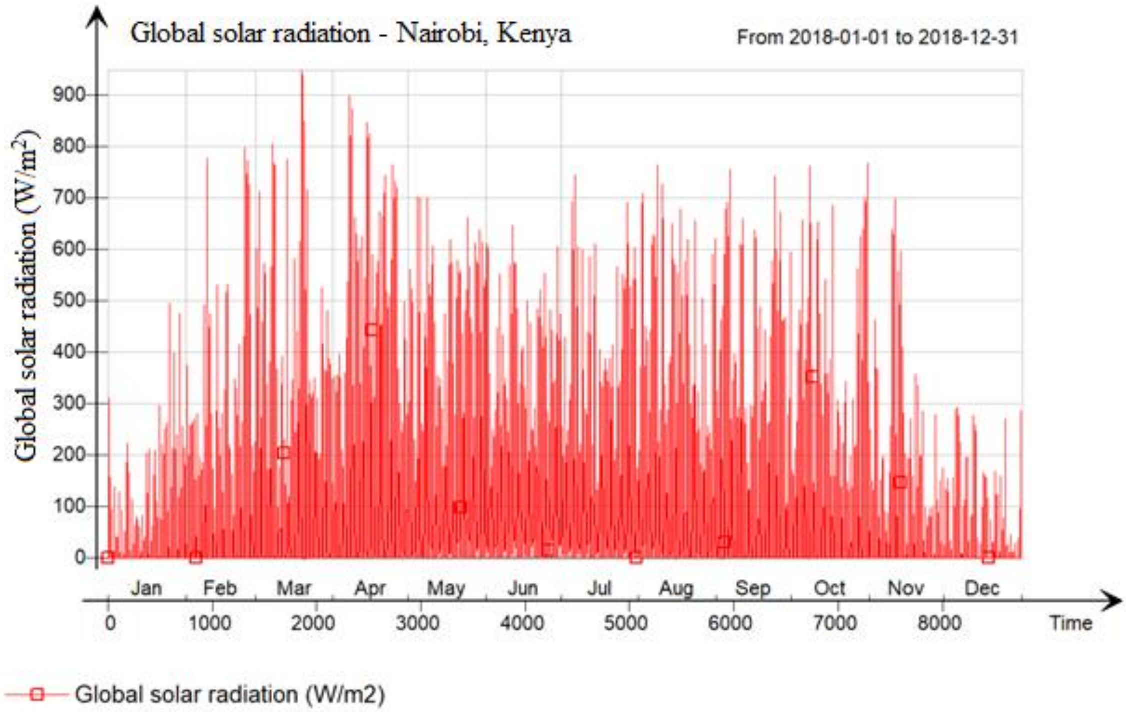

Fig.128. Global solar radiation as a function of time for Nairobi, Kenya.

Table 100. Sensitivity analysis for ECW – Sun – Range 0-100 – Nairobi, Kenya. The table shows the impact on delivered energy for different global radiation thresholds divided into heating, cooling, equipment and lighting.

ECW - Sun - Range 0-100 - Nairobi, Kenya

Window technology	Global radiation (W/m²)	Heating	%	Cooling	%	Equipment	%	Lightning	%	Total	%
ECW Sun	50	700	99%	2174	94%	392	100%	70	756%	3335	98%
ECW Sun	100	681	96%	2218	96%	392	100%	63	682%	3353	98%
ECW Sun	200	655	93%	2582	112%	392	100%	51	548%	3679	108%
ECW Sun	300	629	89%	3623	157%	392	100%	27	291%	4670	137%
ECW Sun	400	615	87%	4390	190%	392	100%	14	156%	5411	158%
ECW Sun	450	612	86%	4780	207%	392	100%	9	99%	5793	169%
ECW Sun	500	614	87%	4901	212%	392	100%	8	82%	5914	173%
ECW Sun	600	613	87%	4935	214%	392	100%	8	81%	5947	174%
ECW Sun	700	613	87%	4935	214%	392	100%	8	81%	5947	174%
ECW Sun	800	613	87%	4935	214%	392	100%	8	81%	5947	174%
ECW Sun	900	613	87%	4935	214%	392	100%	8	81%	5947	174%
ECW Sun	1000	613	87%	4935	214%	392	100%	8	81%	5947	174%
Ref. window	N/A	708	100%	2311	100%	392	100%	9	100%	3419	100%