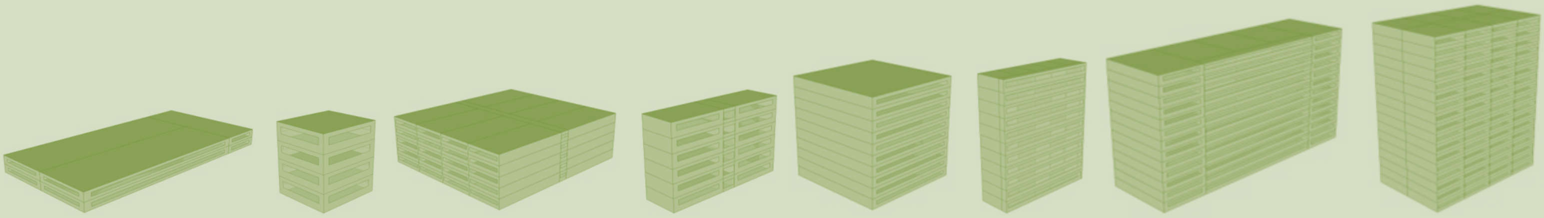
Doctoral Thesis

EVELISE LEITE DIDONÉ

Parametric study for **net zero energy building strategies** in Brazil considering **semi-transparent PV windows**



Karlsruhe Institute of Technology – KIT
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Parametric study for net zero energy building strategies in Brazil considering semi-transparent PV windows

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To my grandfather,
I will miss our conversations on the balcony.
Thank you for your time!

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Declaration

I certify that the work in this thesis entitled "Parametric study for net zero energy building strategies in Brazil considering semi-transparent PV windows" has not previously been submitted for a degree in this or any other University. I also certify that the thesis is an original piece of research and it has been written by me. Any help and assistance that I have received in my research work and the preparation of the thesis itself have been appropriately acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis and the regulations of the university of Karlsruhe (KIT) about good scientific practice have been obeyed.

Karlsruhe, June 2014.

Evelise Leite Didoné

Abstract

The percentage of energy consumption of buildings relative to the overall energy use has grown significantly due to the rising amount of electrical devices used. As one of the main energy consumers, the building sector has an unrealized potential for significant energy savings. The main objective of this work is to develop strategies to transform typical Brazilian office buildings, built in different climatic zones into zero energy buildings (ZEB). Special emphasis is placed on photovoltaic (PV) application, especially the new technology of semi-transparent PV windows. PV modules play an important role in achieving a Brazilian zero energy building scenario, due to their energy generation characteristics, the large amount of incident solar radiation and their constantly decreasing price. These findings were based on parametric computer simulations using Daysim and EnergyPlus programs. The study had four key foci; firstly, semi-transparent PV windows were evaluated as an alternative technology for energy generation and conservation in office buildings. Secondly, the application of various strategies to transform Brazilian office buildings into ZEBs was evaluated. Thirdly, different office building types were investigated and evaluated in regards to their potential to become ZEBs. Finally, the influence of urban environments on a building`s energy generation and conservation was examined. The results reveal that a building envelope design that matches the building's loads and resources is crucial for becoming a ZEB. The use of building integrated PV proved to be a promising option in the replacement of traditional materials. When considering semi-transparent PV windows, some caution should be taken due to the potential hazards caused by the high cell temperatures. An urban environment has a strong influence on a ZEB. Considering the environment, it is likely that the facade of the lower floors is inappropriate for the installation of PV modules. In these places they can be replaced by conventional construction materials. Though buildings with few stories have a better chance to become ZEB in general and especially in an urban context, high rise buildings can be ZEB as well. Altogether the type of urban layout as well as the relationship between net floor area and installed PV power have a big influence on the preferable ZEB type.

Keywords: semi-transparent PV windows, zero energy buildings (ZEB), computer simulation, (sub)tropical climate, office building type

Zusammenfassung

Im Verhältnis zum globalen Energieverbrauch, ist der Energieverbrauch von Gebäuden stark angestiegen. Dies liegt hauptsächlich an der immer größeren Anzahl elektrischer Geräte, die in Gebäuden eingesetzt werden. Als einer der größten Energieverbraucher bietet der Gebäudesektor daher ein großes Potential für Energiesparmaßnahmen. Das Hauptziel dieser Arbeit ist die Entwicklung von Strategien zur Umwandlung typischer brasilianischer Bürogebäude in verschiedenen klimatischen Zonen in Null-Energiegebäude. Speziell sollen dabei die Einsatzmöglichkeiten von Photovoltaik-Modulen (PV) im Allgemeinen und im Besonderen die seit kurzem verfügbaren halb-transparenten PV-Fenster berücksichtigt werden. Insgesamt ist die PV Technik ein wichtiger Baustein in einem Null-Energiekonzept für brasilianische Bürogebäude. Dies liegt an der hohen verfügbaren Solarstrahlung und an den stetig fallenden Investitionskosten. Die Ergebnisse der Arbeit basieren hauptsächlich auf Computer-Simulationen, die im Wesentlichen mit den Programmen *Daysim* und *EnergyPlus* durchgeführt wurden. Als erstes wurde der Einsatz von halb-transparenten PV-Fenstern zur Energiegewinnung in Bürogebäuden untersucht. Dann wurden verschiedene Strategien für die Umwandlung typischer Bürogebäude in Null-Energiegebäude an mehreren Gebäudetypen angewandt und evaluiert. Als drittes wurde die Eignung unterschiedlicher Gebäudetypen für die Umwandlung in Null-Energiegebäude untersucht und als letztes wurde der Einfluss der umgebenden Gebäude auf ein Null-Energiegebäude, insbesondere auf die erzeugte Energie, betrachtet. Die Ergebnisse zeigen, dass eine an die vorhandenen Gegebenheiten angepasste Gebäudestruktur elementar wichtig ist für Null-Energiegebäude. Außerdem hat sich gezeigt, dass gebäudeintegrierte PV Module eine intressante Alternative zu herkömmlichen Gebäudematerialien im Bereich der Null-Energiegebäude sind. Allerdings muss beim Einsatz von PV-Fenster auf die von den hohen Temperaturen der Fenster ausgehenden Gefahren geachtet werden. Desweiteren hat sich gezeigt, dass in einer städtischen Umgebung die Fassaden der unteren Stockwerke meist nicht für einen Einsatz von PV-Modulen geeignet sind. Dort sind herkömmliche Konstruktionsmaterialien meist besser geeignet. Ein weiteres Ergebnis ist, dass es meist einfacher ist niedrige Gebäude in Null-Energiegebäude umzuwandeln. Allerdings hat die umgebende Bebauung und das Verhältnis von Nutzfläche zur installierten PV-Fläche einen wesentlichen Einfluss auf die Machbarkeit. Es konnte zudem gezeigt werden, dass höhere Gebäude durchaus in Null-Energiegebäude transformiert werden können.

Schlüsselwörter: halb-transparente PV-Fenster, Null-Energiegebäude, Computer-Simulationen, (Sub-)tropisches Klima, Bürogebäude Typ

Contents

1 Introduction

Nowadays renewable energies contribute 42 % to Brazil’s energy mix, which is a high value compared to the world's average of 13 % [118]. However, the main source of renewable electric energy is hydroelectricity (77 %). These centralized power plants have limited capabilities to grow and the long distances between the generation facilities and the consumption centers cause high investment costs and energy losses. Additionally, the construction of large scale hydroelectric power plants has serious environmental impacts and in the last years there are growing protest movements against these projects [20], [124].

In times with high energy demand and low water reservoirs, as well, in cases of short-circuits in transmission lines, large area blackouts occur affecting many major Brazilian cities, as happened in 2013 [133]. Solar energy can be used as a complementary power supply offering on-site production, helping to economize water and use less fossil fuel for thermoelectric power plants. The country receives 1,013 MWh of solar radiation, which is equivalent to 50,000 times the annual electricity consumption [117]. Nonetheless, investments in solar energy are still higher in Germany than in Brazil. Only 0.001 % of the Brazilian energy mix is delivered by solar energy [118]. In contrast, in Germany, the nation with the largest installed PV power, around 5 % are produced by solar energy [13], [182].

One way to stimulate the use of solar energy in Brazil is to encourage building owners to install photovoltaic (PV) technology on buildings. In Brazil, the existing buildings account for over 47.6 % of the electricity consumption distributed among the residential (23.6 %), commercial (16 %) and public (8 %) buildings [118]. In the case of commercial and public buildings, air conditioning and artificial lighting are the main consuming systems [136]. A high growth of the energy demand is predicted due to the stable economy, combined with the growing middle-class, which increases the access of the population to new technologies.

The buildings sector has high electricity consumption, but also a high potential for savings. Reduction in energy consumption in existing buildings can be achieved with the implementation of energy retrofit measures [34]. For new buildings, incorporating energy-efficient technologies from the initial conception of the project, the savings can exceed 50 %, compared to a building designed without the use of these technologies [98], [136].

A large number of office buildings in Brazil do not adequately use the available natural resources. A lot of these buildings were projected prioritizing their aesthetic value using characteristics of international architecture that are inappropriate for the local climate. Designing buildings with minimal energy consumption requires combining climate adapted construction strategies with renewable energy sources, such as photovoltaic (PV) modules. By this means buildings can save and generate energy and it is possible to reach an equalized energy balance. Such buildings are called zero energy buildings (ZEB). The concept of ZEB has already been proved for countries in Europe and the United States (U.S.) [69], [122].

Photovoltaic elements have numerous application possibilities in a ZEB scenario, due to their energy generation characteristics and constantly decreasing price. Their price development actually makes them competitive to other building materials [156] and they are technically seen a reasonable way to achieve an equalized, i.e. zero energy balance. PV panels can be applied / integrated into roofs, facades or replace elements such as shading devices. Currently, a wide variety of photovoltaic modules using different technologies are available on the market offering a broad range of options for architects. This offers the possibility to use them not primarily for energy generation but also for aesthetic reasons, whereas the generation of electricity is just a benefit.

The energy generation period of PV panels is well suited for office buildings, whose occupation period and highest energy consumption are in the daytime, the same time when the PV modules produce electricity. Excess energy can be fed into the electric network. In multi-storey office buildings the available area for PV installation is limited. The building envelope might not be sufficient to fulfill the building’s energy needs, using conventional PV application. In this case, it is necessary to investigate other possibilities for their suitability and for aesthetics considerations.

One possibility is the replacement of tinted glass or dark plastic film covered windows with semi-transparent PV windows, which are common beneath clear glass windows in cooling dominated multi-storey office buildings [31], [173]. Semi-transparent PV windows have a significant potential to reduce the annual electrical consumption for cooling and in addition generate energy. However, some care should be taken with buildings located in urban areas, since parts of the buildings envelope can be shaded which should be avoided in order to not reduce the PV module efficiency. In the case of net ZEB, PV installations also might be used close to the building or building clusters ('on-site' or 'nearby' energy generation) in an urban context, or in a larger scale as Landscape Integrated PV (LIPV) ('at site' energy generation), which make the creation of self-sufficient cities possible.

This thesis investigates possibilities for the transformation of typical Brazilian office buildings into zero energy buildings using established energy consumption reduction methods and photovoltaic technologies (on-site). The difficulty for transforming multi-storey buildings into ZEB arises from their number of storeys with a high specific electricity consumption compared to their relatively small envelope, offering few possibilities for PV application. One of the main contributions is the development of a required ratio between installed PV potential, the building energy balance and its surface.

1.1 Research objectives

The main objective of this research is to develop strategies to transform typical Brazilian office buildings in different climate zones into ZEB with special respect to PV application in general and especially the new technology of semi-transparent PV windows.

To systematically evaluate influencing factors the research was split into several key aspects that were examined separately and then integrated into the main concept. These aspects are:

- Definition of a methodology for the evaluation of semi-transparent PV windows in Brazilian office buildings using building simulation tools;
- Evaluation of the influence of semi-transparent PV windows on the building energy consumption considering the use of daylight, power conversion efficiency (PCE) and transmittance;
- Transformation of office buildings types into net zero energy buildings;
- Examination of different multi-storey office building types for the definition of appropriate zero energy building volumetries;
- Analysis of the load matching and grid interaction of PV equipped office buildings;
- Determination of the influence of the urban context on the solar irradiation and generated electricity.

1.2 Thesis structure

This thesis is organized in six chapters. The current chapter presents a brief introduction to the investigated problem and states the pursued objectives of this thesis.

Chapter 2 comprises a review of literature related to the subjects of this thesis. It starts with the energy conservation methods for Brazilian and German buildings. Then, the relationship between photovoltaic and architecture is presented with an emphasis on new applications and technologies for building integration. The chapter ends with an introduction of net zero energy buildings, their definition, energy balance, design limits and the role of PV technology in net ZEBs.

Chapter 3 outlines basic parameters used within this research. The chapter focuses on the climatic characteristics of the selected simulation locations, i.e. cities; representative office building model with its fixed and variable parameters; and introduces the main tools used for building simulations.

Chapter 4 describes the procedure used for the transformation of different building types into zero energy buildings. At first, a study analyzing the potential of semi-transparent PV windows for energy reduction and generation, including daylight performance and a sensitivity analysis between the transmittance and the efficiency of the PV is presented. Afterwards, strategies used for the transformation of a typical Brazilian office building into a ZEB are shown. This made it possible to analyze the potential of different building types to reach ZEB status. Finally, the influence of the urban context on the achievable energy generation is investigated.

In chapter 5 the results of the computer simulations are presented and discussed. For the zero energy office buildings, also the optimal and zero energy building models developed by the application of defined strategy and the overall on the envelope applied PV modules for the different building types are shown. The last, chapter 6 is dedicated to the conclusions and recommendations for future work.

2 Background

In this chapter the state of the art of zero energy buildings and the applied PV technologies prior to this thesis are presented. Firstly, energy conservation techniques in buildings focusing on Brazil and Germany and current regulations for energy efficiency in buildings are described. Secondly, an overview about photovoltaic technologies and their application in buildings are shown. Finally, definitions for net zero energy buildings and evaluation methods are presented.

2.1 Energy conservation in buildings

Buildings are today responsible for nearly 40 % of the globally used final energy [180] and the percentage of their energy consumption is growing due to poor design, inadequate technology and inappropriate behavior. However, opportunities exist to reduce the buildings' energy use at lower cost and with higher revenue than in other sectors

To reduce excessive energy use in new buildings a variety of energy-efficient technologies and practices are being developed and implemented in many countries. This section gives a review about the Brazilian measures and regulations for raising the energy efficiency of buildings and draws a comparison to the developments of Germany, a country with extensive research in this field.

2.1.1 Brazilian context

A major step towards greater energy efficiency in Brazil was the approval of the law N° 10,295 on October 17, 2001 [23]. This act strengthened Brazil’s national electricity conservation program (PROCEL) which launched its energy efficiency action plan for buildings (*PROCEL-Edifica*) in 2003.

One of the outcomes of this plan was the energy efficiency labeling system called Technical Quality Regulation on the Energy Efficiency of Commercial, Services and Public Buildings (*Requisitos Técnicos da Qualidade para o Nível de Eficiência Energética em Edifícios*

Comerciais, de Serviços e Públicos - RTQ-C), published in 2009 [24] and subsequently in 2010 the Technical Quality Regulation on the Energy Efficiency of Residential Buildings (*Regulamento Técnico da Qualidade para o Nível de Eficiência Energética em Edifícios Residenciais* - RTQ-R) [25]. Both Regulations define a methodology for classifying the energy efficiency of buildings, with a distinguished process for non-residential and residential buildings.

These regulations are complemented by the requirements for the assessment of the conformity of the energy efficiency of buildings (*Requisitos de Avaliação da Conformidade para Eficiência Energética de Edificações* - RAC) [26], which details the evaluation process of building and is used to grant the national energy conservation label (*Etiqueta Nacional de Conservação de Energia* -ENCE).

The RTQ aims to qualify and quantify the electric energy consumption of buildings in Brazil. The proposal is to specify the technical requirements and methods for classifying buildings according to their energy efficiency. It is expected that the regulation helps reducing the energy consumption by defining a minimum energy efficiency level, which is evaluated through computer simulations or prescriptive methods. The levels vary from A (most efficient) to E (least efficient).

For commercial, public and services buildings the regulation covers three aspects of the buildings: envelope, lighting and air conditioning, with different weights for each aspect: 30 %, 30 % and 40 %, respectively. For residential buildings other factors are considered, these are the envelope, considering summer and winter periods, and the water heating system. In the common area of multi-family buildings, lighting, elevators and water pumps are evaluated. Both regulations also consider other strategies, for example, the use of natural resources (daylight and natural ventilation) and renewable energy sources.

Besides these regulations, international certifications like Aqua[1] and LEED[2] were adapted to the Brazilian reality. The *Selo Casa Azul Caixa* is a voluntary certification promoting sustainable residential constructions supported by the Brazilian bank *Caixa Economica Federal* (CAIXA). It is the first Brazilian certification for sustainable house developments [29].

In 2011 was the solar seal (*Selo Solar*) developed by the institute for the development of alternative energy in Latin America (Ideal) with support from the German cooperation for

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[1] Aqua certification (High Environmental Quality), launched by Carlos Alberto Vanzolini, the accreditation is based on the French system HQE with indicators adapted to the Brazilian reality.

[2] The LEED label (Leadership in Energy and Environmental Design) is a green building certificate from the United States developed by the USGBC (United States Green Building Council). It is a globally accepted classification system adapted and recognized by the Green Building Council Brazil.

sustainable development through the *Deutsche Gesselschaft für Internationale Zusammenarbeit* (GIZ) GmbH and the German development bank (KfW). The seal has the aim to encourage the use of solar energy (PV) in Brazil [83].

The application of photovoltaic technology in Brazil began to be discussed at the beginning of the decade. However, the first system was installed in 1997 by the research group on strategies for the application of solar energy (*Estratégica em Energia Solar* / FV-UFSC) at the Federal University of Santa Catarina (UFSC) [146]. Other systems have been installed at the Universities of Sao Paulo (USP), Rio Grande do Sul (UFRGS) and Para (UFPA), as well as research institutes and utilities. The installed PV system helps to generate energy for the building, but the energy balance does not reach zero. Meanwhile, new projects have been developed such as the design of solar energy powered stadiums for the soccer World Cup 2014 and solar energy powered airports.

Another advance was the approval of the resolution N° 482 created by the national electric energy agency (ANEEL), in April 2012. The resolution regulates the micro and mini-generation of electric energy by consumers, and aims to reduce the barriers for the installation of small distributed energy generation facilities, i.e. micro-generation plants up to 100 kW and mini-generation plants from 100 kW to 1 MW [10]. This means anyone can generate electricity for his private use, and the excess energy can be exported to the electricity network to reduce the energy bill. Until the termination of this thesis in Brazil existed only 86 central solar PV electricity generation plants [11].

Until now, net ZEBs do not exist in Brazil. From an economic point of view on-site energy generation out of renewable resources such as solar and wind energy, still suffer from high investment costs. However, two ZEB buildings were developed within university projects: the CECAS, building that will be the center for the study of climate and sustainable environments at the University of Sao Paulo, and the EKO House. The latter one participated in 2012 at the Solar Decathlon in Europe [157]. This is an international university competition with the aim to design innovative energy-efficient houses that are supplied solely by sun energy.

2.1.2 German context

Germany first introduced thermal performance requirements in 1977 [70] and in 2002 unified requirements for the energy performance of insulation and heating systems, for new and existing buildings and a compulsory energy certificate for new buildings and major renovations [151] were established.

The building codes have been strengthened six times over the past 35 years and an energy demand reduction for heating and hot water provision has been achieved, from 300 kWh/(m^{2}y) to almost 65 kWh/(m^{2}y) [62]. The development of the energetic demands of buildings in Germany with minimal energetic requirements, high performance pilot projects and innovative buildings can be seen in Figure 2.1.

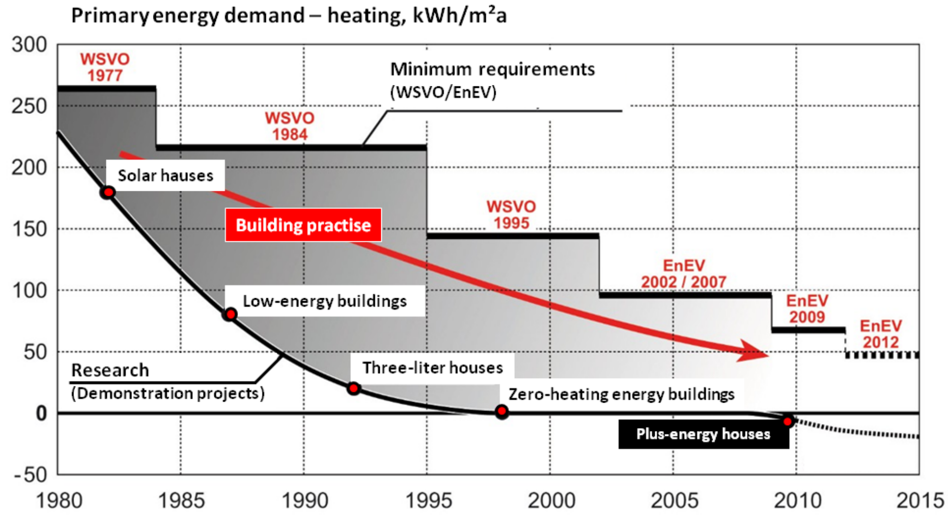


Figure 2.1: Energetic development of buildings in Germany. Copyright Hans Erhorn, Fraunhofer IBP. Translated from [67].

The Energy Conservation Ordinance "*Energieeinsparverordnung*" (EnEV) and its amendments (EnEV 2002, EnEV 2009, EnEV 2012 and EnEV 2014) are an important part of the energy and climate policy of the German Government [174]. The legislation prescribes minimal energetic requirements of buildings and building components for new buildings and for major renovations. Additionally framework conditions and mandatory certificates are defined in this regulation.

The energy efficiency according to the EnEV standard is determined by measuring the annual primary energy requirements of a building as well as the thermal insulation of the building envelope. Compared with the last version of the EnEV, the primary energy requirements in the 2009 amendment were increased by approximately 30 % and the useful energy requirements, i.e. insulation, were increased on average by 15 %.

The standard of requirements for saving energy has been constantly raised at shorter intervals over the recent years. The EnEV 2009 reduced the limits that were set out in EnEV 2002 by approximately 30 % and the EnEV 2012 by another 20 %. Discussions about a further amendment (EnEV 2015) are currently taking place [54]. An example of the actual energy certificate can be found in [48]. Except the EnEV another regulation dedicated to the use of renewable energy for heating has been released in 2009 and adapted in 2012 (*Erneuerbare-Energien-Wärmegesetz* [27]).

On 19th of May 2010, the European parliament and the council approved a reformation of the Energy Performance of Buildings Directive (EPBD), which was firstly released in 2002, and determined that by the end of 2020 EU member states must ensure that all newly-constructed buildings consume 'nearly zero' energy and that their energy needs must be met, to a significant extent, by renewable energy sources, including on-site or nearby produced energy [64].

The public authorities are requested to set an example by owning or renting only these kinds of buildings by the end of 2018 and by promoting the conversion of existing buildings into the 'zero' or at least 'nearly-zero' energy buildings [65] – though the standard still has to be defined in detail on a European and a national level. Until 2015 the Member States must improve the energy performance of new buildings [64]. For the intermediate target the passive house standard has to be applied [153].

A passive house generally indicates a house in which passive systems are used as the main means to provide light, heat and ventilation [128]. In the extended definition of the passive house, not only the energy demand for heating is included, but also the demand for domestic hot water and energy for electric appliances. A high number of low energy buildings have already been built in Europe [21].

2.2 Photovoltaic and architecture

Among the different renewable energy sources, photovoltaic exhibit certain features that make them particularly suitable for applications in urban environments. The silent and zero-emissions PV modules can be installed directly on the building where the energy is needed. The PV components can be applied to buildings in different ways: as building-added / attached PV (BAPV) and as building-integrated PV (BIPV). BAPV products require additional mounting systems and are typically used for retrofits, whilst BIPV products become an integral part of the building envelope and can substitute envelope components entirely. Both concepts must take into account constructional, energetic and architectural aspects to the same extent.

In principle, it is possible to use photovoltaic modules on all building surfaces that are directly exposed to sunlight. PV modules can be used for the generation of electricity e.g.

on / in roofs as opaque or semi-transparent envelope surfaces or as a sun shading and have a structural function consequently reducing construction costs [66]. Figure 2.2 shows schematically the principal PV installation options for roofs, facades and sunshades and in Figure 2.3 some pictures of application examples are presented.

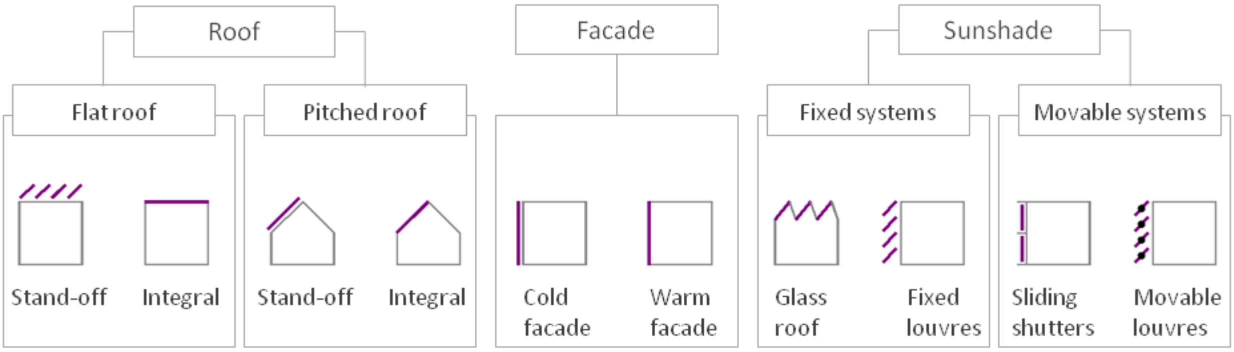


Figure 2.2: PV installation options for roof, facade and sunshade, adapted from [181].


(a) (b) (c)

Figure 2.3: Examples of PV application for roofs (a), facades (b) and sunshades (c).

A building-mounted PV system has a relationship with the building on which it is mounted and with the urban or rural landscape surrounding. Therefore the visibility of the PV installation plays an important role, e.g. reflections from buildings can affect traffic safety and the pedestrians' perspective should also be considered. Facade-integrated PV on dominant urban structures, e.g. high-rise buildings, must be contemplated with respect to their appearance within the city skyline. Additionally, designers must consider building regulations, which prescribe the approved types, sizes and orientations of structures, and roofs.

Due to technological and aesthetical improvements of PV modules, and because of the increased interest in renewable energy, PVs are nowadays accepted by public and architects.

This change of attitude makes it possible to use PV technology in buildings according to architectural considerations, which generates new architectural and market demands [115].

2.2.1 State of the art and new applications

The use of PV in buildings is investigated since more than 20 years now [82]. However, in the last five years, this technology has been the fastest growing segment of the electricity power generation market [142]. The possibility to install PV modules right where the energy is needed and the continuously decaying price makes them ideally suited for the installation in urban environments.

From a technical point of view, the use of PVs in buildings is an interesting option, as they can be placed on existing surfaces or even replace them. Nevertheless, their application is not an easy task, due to their great influence on the building aesthetic. As a consequence of the animosity of the public towards PVs, a lot of research has been directed towards making PVs physically more appealing, and technologically easy to use. Thanks to the research carried out in the recent years, PVs have changed from an electricity generator stuck on top of buildings to an increasingly aesthetic element of buildings [115].

The potential of different building types (i.e. residential and non-residential buildings) with PV integration, as well, remarks on the building design process to optimize the energetic performance and to maximize the PV contribution to the buildings' energy use, can be found in literature [78], [90], [148], [172], also the application of the new thin film PV technology and components using it, i.e. (semi-)transparent PV (STPV) glazing are reported.

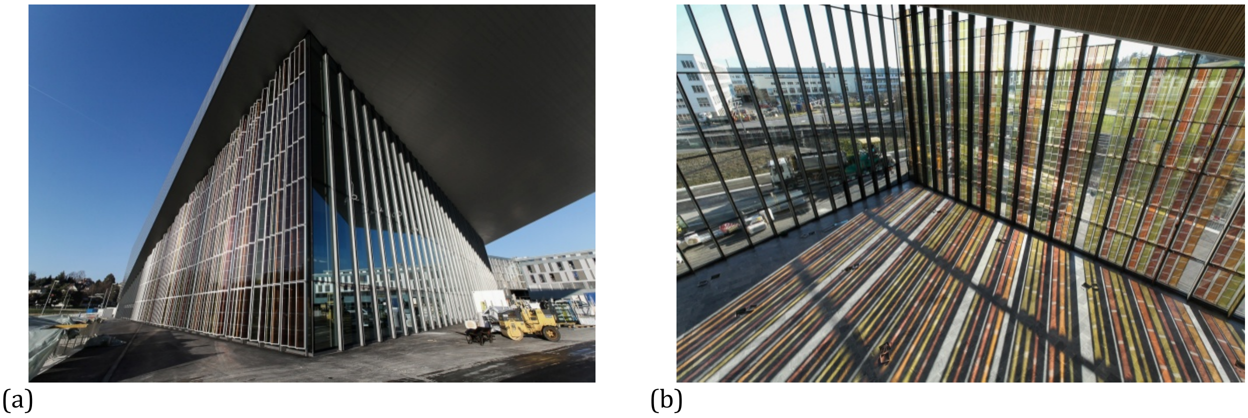
Thin film PV technologies offer various new options for PV application. A number of different module designs are available. Nonetheless they can be substantially divided into PV glasses, sheets and roof membranes. Glasses are produced with different dimensions and transparency, allowing the designer a good daylight and thermal control, whereas sheets and roof membranes can be fabricated with different dimensions and applied to numerous materials ensuring their compability with traditional roofing systems. The great flexibility of thin film PV modules, with the possibility to freely define their shape can be the tool to transform architectural objects into energy generators [115].

Practical and theoretical applications using (semi-)transparent PV modules on the facade employing different PV technologies have already been published [37], [68], [145], [163], [183], [184]. Semi-transparent PV modules are created by using transparent materials, e.g. glass, for the encapsulation of the cells and for the construction of the module. The module itself can be constructed in many ways: single, double or triple glass panes, with the position of the PV cells at the rear of the front pane or in front of the back pane [22]. PV modules composed of tiles of conventional multicrystalline or monocrystalline silicon cells in a sandwich of glass panes are already available on the market. These modules can be applied on the facade with different spacings of the PV cells. The optimal cell spacing and its impact on the thermal and visual comfort, as well as the energy generation have already been investigated for crystalline cells [22], [68], [114], [145], [183] and for amorphous silicon thin-film PV modules [37], [163], [184]. In addition a cost analysis of semi-transparent PV modules used in skylight and as facade elements for office buildings has been made [99], [100].

Semi-transparent PV modules simplify the use of daylight in buildings as their transparency depends on the PV type used and can be influenced within certain constraints. Currently, STPVs are gaining their niche and are widely use for PV facades in non-residential buildings. Current research include energy savings by the use of semi-transparent PV windows [116], thermal and optical aspects [75], [179], energy performance of single-glazed [104], double-glass [76], [101] and ventilated PV windows [35], [36], as well as their use in cooling and heating dominated climates [38], [73].

The use of see-through solar cells is suitable for places where people spend shorter periods of time [167]. However, organic PV cells, such as dye-sensitized (DSSC) and organic PV (OPV) technologies are recognized for their possible uses in large-area, flexible, and low cost power generation applications. They can be integrated into window panes in houses, high-rise buildings and automobiles, enhancing the functionality of transparent surfaces. Prototypes of the newest STPV, the OPVs have been fabricated with a visible transmittance higher than 55 % which is sufficient for their use on architectural glass [17], [97], [105]. Thus window integrated PVs for automotive and building applications are a promising market segment for these organic PV modules though they currently have a quite low power conversion efficiency of only 3 %. Their big advantage is a remarkable transparency with an outstanding color transmission very close to neutral density filters, i.e. giving a very natural white light color perception. The transmittances of OPVs can be adjustable by variation of the active layer thickness [39].

A real world example for the application of OPV modules is the west facade of the École *Polytechnique Fédéral de Lausanne* (EPFL) Convention Center (Figure 2.4) [18] in Switzerland, which has a large semi-transparent PV facade, with translucent and colored photovoltaic panels (dye-sensitized solar cells). The PV modules are at the same time decoration, shadowing device and generating energy. The building's facade has 1,400 solar modules, each one with a size of 35 cm by 50 cm creating a total surface area of 300 m^2. Aside the fact that translucent solar cells have lower efficiency which is inherent to their design and purpose, the efficiency of the DSSC has dramatically increased from 4 % to 15 % [28].



(a) (b)

Figure 2.4: Outside (a) and inside view (b) of the innovative facade of the SwissTech Convention Center at *École Polytechnique Fédéral de Lausanne.* Copyright: STCC - EPFL, 2014 [166].

From an architectural point of view this is an excellent example where BIPV have a great aesthetical value. In terms of energy generation, their contribution to the overall building demand is secondary. Summarized, the significantly falling module costs offer the possibility to use PV modules not primarily for energy generation but also for aesthetic reasons, whereas the generation of electricity is just a benefit.

2.2.2 Technologies for building integration

The currently available PV products used on buildings are normally based on prefabricated composite modules assembled of various materials. There are two fundamentally different approaches for the use of PV technology. One is the conscious exploitation of the modularity. The whole spectrum of design options for the modules with respect to form, color, light transmittance and cell arrangement can be used on the building envelope to generate, larger sized patterns.

On the other hand, some building tasks demand small-scaled elements with a homogeneous texture and unobtrusive coloring. These requirements are best met with thin-film technology elements. Organic PV cells which already exist in the laboratory can become an attractive opportunity in future. It might be possible to apply them to various substrates in the form of paints, varnishes or inks - expanding the design options and the applications for building-mounted PVs [181].

The development of building integrated PV (BIPV) systems follows the general development of PV modules. The evaluation of BIPV products involves, among others, properties such as solar cell efficiency, open circuit voltage, short circuit current, maximum efficiency and fill factor. It is expected that BIPV systems will improve further as PV modules do in general. Rising efficiencies and decreasing prices can be expected. Information about a variety of BIPV products with a representative selection of the state-of-the-art, such as, foil products, tile products, module products and solar cell glazing products can be found in [66], [74], [130]. A future vision of painted PV applications can be found in [130].

2.3 Net zero energy buildings: a new perspective

In recent years, the topic of Zero Energy Buildings (ZEB) has received increasing attention. In 2010, the European Commission and Parliament adopted the recast of the Energy Performance of Buildings Directive (EPDB) which requires that by the end of 2020 all new buildings shall be "*nearly zero energy buildings*" [64]. The U.S. Department of Energy (DOE) has established to achieve "*marketable zero energy homes in 2020 and commercial zero energy buildings in 2025*" [53].

According to the EPDB [64] the term "*nearly zero-energy building*" describes a building that has a very high energy performance. The remaining required energy should be covered to a bigger part by energy from renewable sources, produced on-site or nearby. While, according to U.S. Department of Energy [53] a "*net-zero energy building*" is a residential or commercial building with greatly reduced needs for energy through efficiency gains, with the balance of energy needs supplied by renewable technologies.

Until early 2011 no national energy code explicitly defined a net ZEB [176]. However, many authors have been discussing about the definition and different concepts on how to calculate the annual energy balance for net ZEBs [69], [80], [109], [110], [119], [127], [149], [150], [171], [176]. Four commonly used definitions for low-energy buildings are: net zero site energy, net zero source energy, net zero energy costs and net zero emissions [171]. For other authors a net zero energy building simply has a neutral energy or emission balance over the period of one year [149], [176].

In the long term, the life-cycle energy balance of buildings, including their production, maintenance and demolition/disposal should be taken into account for the definitions [176].

The concept of a net ZEB also includes different concepts of supplying renewable energy: on-site renewable, nearby renewable, off-site renewable, purchased 'green' energy from contracts, off-site wind turbines or combined heat and power plants (CHPPs) [110], [111], [150].

For a better understanding of net zero energy buildings several European countries plus U.S., Canada and New Zealand are participating in the project called 'Towards Net Zero Energy Solar Buildings' (IEA SHC Task 40/ECBCS Annex 52) [158]. The objectives of the project are to study current net zero, near net zero and very low energy buildings and to develop a common understanding of a harmonized international definitions framework, tools, innovative solutions and industry guidelines.

A French national research project, named ENERPOS, has focused on the development of new methods and tools for the design of net zero energy buildings in hot climates. The proposed method was applied to the first net ZEB in the French overseas territories. The building was designed to operate as long as possible using passive techniques, such as cross natural ventilation and daylight. The goal of an energy index below 50 kWh/(m^2 year) (which is three times below the mean ratio of local standard buildings) was obtained by computer simulations. The actual energy index after one year of operation was around 31 kWh/(m^2 year), which is even 38 % below the simulation results. The used PV modules supplied 78 kWh/(m^2 year). The efficiency of the design method was proved and has been used by other professionals [69], [98].

The worldwide number of zero energy buildings is growing continuously [122], [175]. With the increasingly available efficient technical solutions, bigger and more intensively used building typologies have been realized as net ZEB since 2009. Most net ZEB projects were realized in north-westerly situated countries and climates. Up to now, the only existing net ZEB of South America is located in Argentina [159].

2.3.1 Energy balance calculation methods

Regarding the various definitions of zero energy buildings it is evident that the definition of the temporal and spatial boundaries significantly influences the degree of sustainability of a building [109]. Anyway even for full life-cycle analysis the granularity of the captured data has to be examined critically. This means even buildings whose life-cycle balance is zero might be not auto sustainable in an hourly analysis.

Therefore different building analysis methods were developed characterizing different aspects of net ZEBs. Examples of net ZEB balance types are load / generation balance and import / export balance [177]. The load / generation balance can be used in the building planning phase. It focuses on the balance between on-site generation and the calculated energy demand. The import / export balance focuses on the annual balance between weighted demand and weighted supply. It is a high-resolution method used to calculate the balance when monitoring (or simulating) a building. The main difference between the two balance types is the energy consumed by the building.

Inside import / export balance, options of analyses are load matching and grid interaction (LMGI) which were developed to describe the energy exchange between net ZEBs and the grid infrastructure. Load matching refers to the relationship between a buildings energy demand and the on-site energy generation and the grid interaction describes the relationship between the energy imported / exported to the grid and its course. The definition for both indicators and examples of their application for different buildings can be found in [147], [168], [178] [160].

2.3.2 Photovoltaic in zero energy buildings

Net ZEBs are changing the way of thinking about energy use. Based on the appraisal that most net ZEBs should or will be located in urban areas, PV technology seems one of the most suitable forms of on-site energy generation. However, the application of PV technology in ZEBs is not discussed very detailed in literature up to now [155], [156]. The existing literature focuses on the location of the generated energy by PV modules in the buildings footprint or on-site and its relationship with the architectural form of the building. In general the situation for buildings with more than two storeys in urban environments is quite complex. The problem is that PVs are usually the only source of renewable energy, the buildings' surface area is limited, the energy demand is high in comparison to the available surface and the conversion efficiency of PV modules is bounded as well.

In those cases, the 'nearby' supply is an option for nearly net ZEBs together with other renewable energy sources. This implies that the issue of PVs in ZEBs should be discussed on the level of the building as well as on the level of building clusters or at an urban scale [79], [88]. An example of a net ZEB cluster is the '*Solarsiedlung Freiburg*' in Germany. The houses were designed as ultra low energy houses (passive houses), consuming very little energy which could be balanced by PV systems on the roofs [79].

3 Building context and simulation tools

This chapter presents basic parameters and computer simulation tools used throughout the thesis. Furthermore the simulation sites, their geographic location and climates are explained, as well as building parameters and simulation tools used for the building analyses.

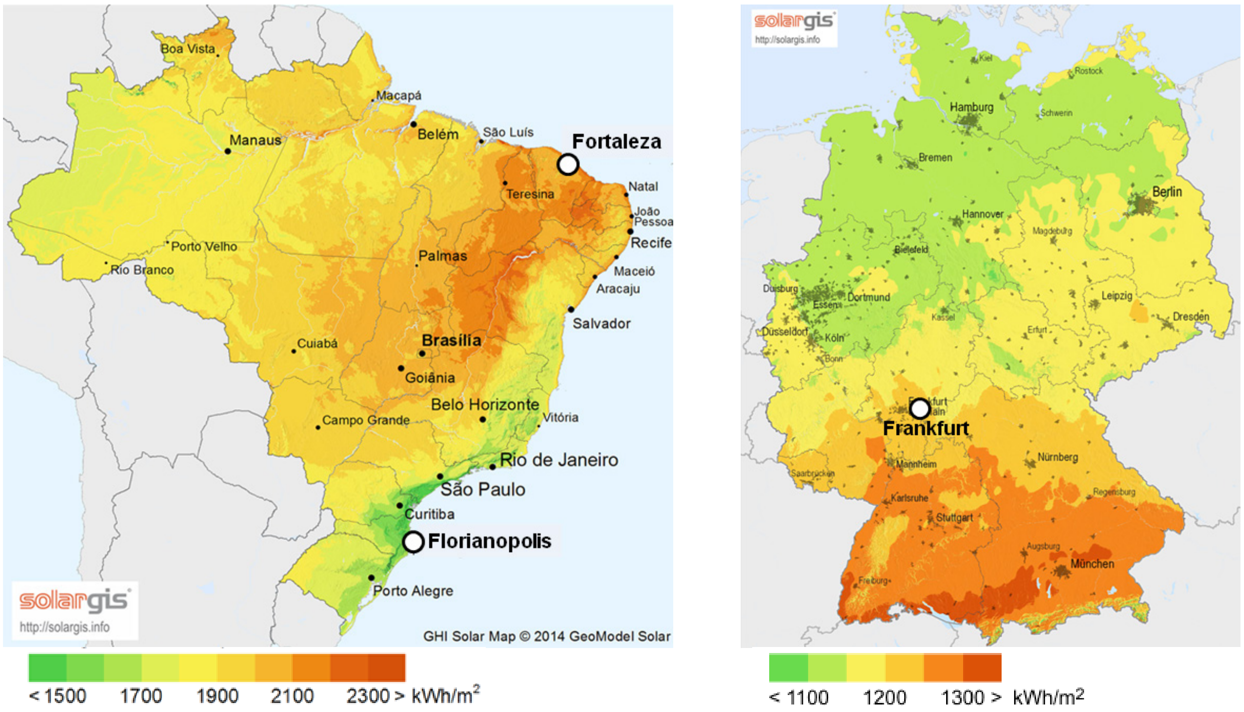
3.1 Climatic characteristics

For the simulations three cities were chosen based on their geographic location and their climatic differences. In Brazil the cities Fortaleza and Florianopolis were selected and in Germany Frankfurt. Although the thesis focuses on Brazilian cities, the German city was chosen for some comparisons due to its moderate continental climate.

Brazil is the fifth largest country in the world and the largest in South America. It has an area of 8,574.761 km^2 and is measuring 4,345 km from its northern most point to its southern tip, and 4,330 km from east to west [84]. The city of Fortaleza/CE is located on the north-east coast of Brazil (3°43'6'' S, 38°32'36'' W). It is one of the Brazilian cities with the highest solar irradiation. It has an average daily irradiation of 5.67 kWh/m^2 day and its climate is classified as tropical savanna (Köppen climate classification: As) [45]. The city of Florianopolis/SC is located in the southernmost part of Brazil (27°35'49'' S, 48°32'58'' W). It is one of the cities with the lowest solar irradiation in Brazil, with an average daily sum of 4.77 kWh/m^2 day, and it has a humid subtropical climate (Köppen climate classification: Cfa) [46].

Germany is located in west-central Europe and it is the seventh largest country on that continent with an area of 357,021 km^2. The country measures 886 km from north to south and 636 km from east to west [49]. The city of Frankfurt is located in central West Germany (50°7'0'' N, 8°40'60'' E). It has a solar irradiation of 3.02 kWh/m^2 day [137] and an oceanic climate (Köppen climate classification: Cfb) [47].

In Figure 3.1 the locations of the cities and their global solar irradiation are presented. According to the data, Florianopolis gains around 20 % more sunlight than the sunniest region of Germany – the nation with the largest installed PV power [142].



(a) (b)

Figure 3.1: Average annual sum of global irradiation on horizontal surface for Brazil (a) and Germany (b). SolarGIS © 2014 GeoModel Solar [162].

The climatic characteristics of the three cities are compared below. The outside temperature and the solar radiation incident on the four facades facing the cardinal orientations (East, North, West and South) are presented in Figure 3.2.

As the cities Fortaleza and Florianopolis are located on the southern hemisphere the winter months are between June and August. Fortaleza has the highest annual average temperature of around 25 °C. Florianopolis, on the southern coast of Brazil, presents temperatures along the year around 20 °C. In the winter months (June-August) the temperatures can be as low as 5 °C. In contrast, in Frankfurt, which is located on the northern hemisphere, the winter months are between December and February. It has the highest temperature range of the three cities, ranging from -9 °C in winter to 33 °C in summer. The maximum temperatures for the three cities are quite similar, they range between 30 °C and 35 °C.

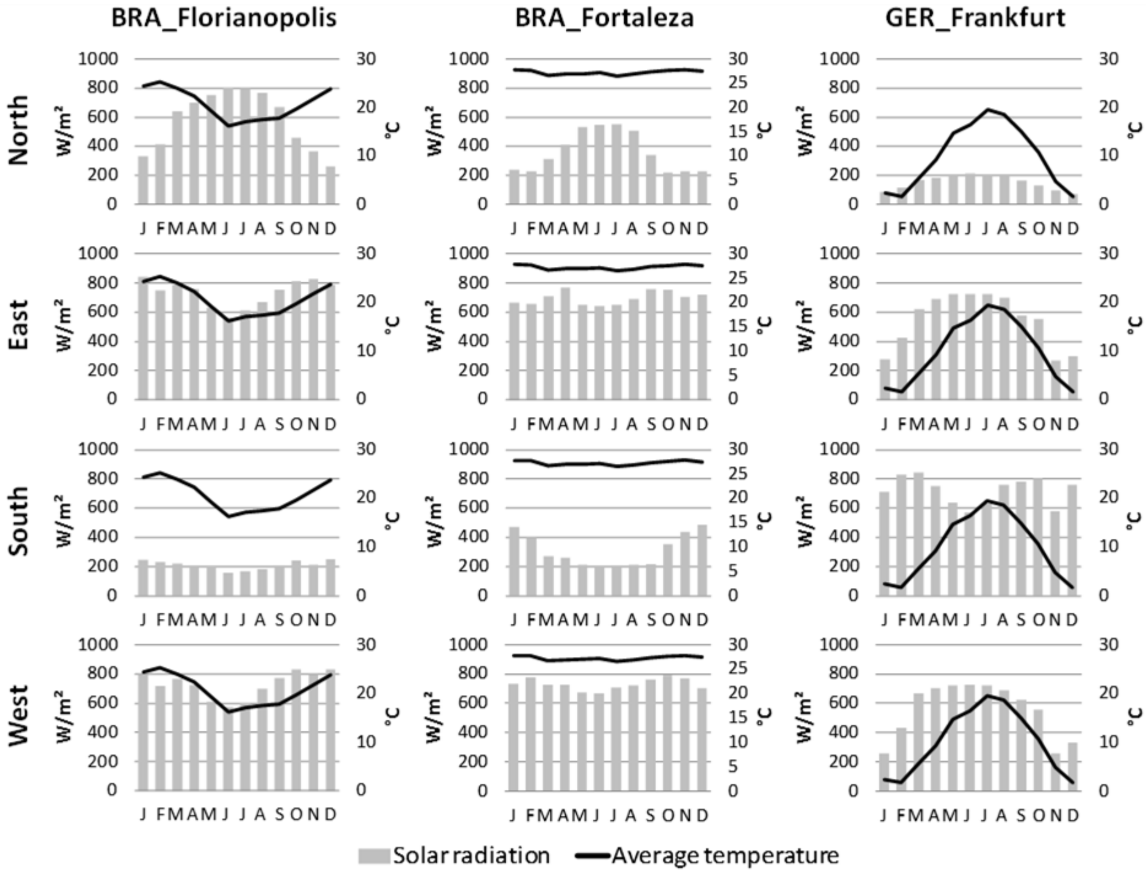


Figure 3.2: Annual behavior of temperature and solar irradiation for the three cities.

The solar irradiation level changes according to the facade orientation. Florianopolis and Fortaleza show a similar behavior but with different levels for the same facade. Frankfurt presents considerably different irradiation intensities compared to the Brazilian cities. The West and East facades show similar levels for the three cities, though the annual change is highest in Frankfurt. In Fortaleza the highest irradiation values are attained for the West facade, in Florianopolis for the North facade and in Frankfurt for the South facade.

The weather files for the three cities, used for the simulations, are available on the website of the U.S. Department of Energy [55]. The weather files provided on the site are TMY2 (Test Meteorological Year) files. These files, resulting from the SWERA project, are a compilation of months from different years without extreme temperatures, generating a climatic year that never existed [43].

3.2 Representative office buildings

As it is not possible to investigate all existing building types, representative models for Brazilian office buildings had to be defined. The characteristics of the representative buildings were determined using data from a literature review [30], [31], [94], [113], [173]. The main building characteristics are: geometry, number of floors, building area, building material, envelope components, number of occupants and internal gains.

The building types are based on researches[3] carried out by *Eletrobrás/PROCEL*[4] and the Federal University of Santa Catarina (UFSC). The study developed datasets for residential, commercial and service building prototypes, which were used for the development of the Brazilian energy efficiency labeling of buildings [24].

The office buildings prototypes were based on the database for commercial buildings defined by an on-site survey of buildings in different cities and regions of Brazil. Around 1103 buildings were evaluated to determine their constructive characteristics and electricity use [30] 35 commercial buildings were analyzed regarding their constructive characteristics and 41 offices in relation to their occupancy and internal gains [173].

The building models defined in these studies were used as prototypes and adapted for the definition of further models. The geometric properties of the buildings were adapted according to the specific studies in this thesis and are presented in the according sections.

3.2.1 Fixed parameters

The parameters presented in this subsection remained constant for all studies and models within this thesis.

3.2.1.1 Occupation and metabolic heat gain

The office rooms have a nominal occupation of 14.7 m^2/person and the hallway is occupied by one person. The metabolic heat gain for office activity according to [16] is shown in Table 3.1.

Zone	**Activity**	**Heat generation in W/m^2**	**Heat generation for a skin surface area of 1.80 m^2/W**	**Met**[5]
Office	Typing	65	117	1.1
Hallway	Walking about	100	180	1.7

Table 3.1: Metabolic heat gain for typical office activities [16].

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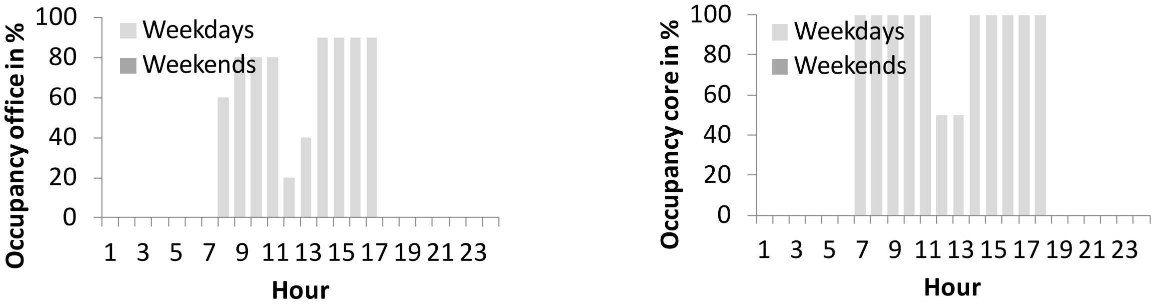
[3] These studies were used for the development of the Brazilian energy efficiency labeling for buildings (RTQ-C and RTQ-R) within the Brazilian labeling program - PBE [24], [25].

[4] Eletrobrás is a major Brazilian electricity producer; PROCEL, *Programa Nacional de Conservação de Energia* (national electricity conservation program), is a program for the rational use of energy developed in 1985 [56].

[5] 1 Met = 58.1 W/m^2 [16].

3.2.1.2 Schedule

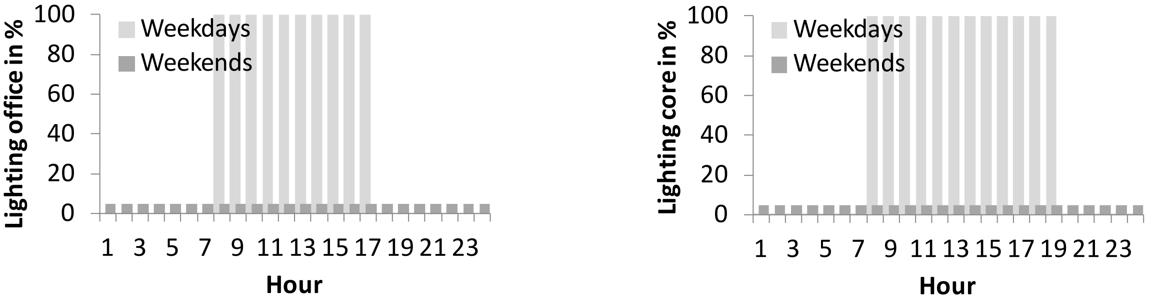
The occupation period for lighting, equipment and HVAC is from 8 a.m. to 6 p.m. (10 h duration) and for the users it is from 8 a.m. to 12 p.m. and from 2 p.m. to 6 p.m. The hallway is occupied from 7 am to 19 pm (12 h duration). In the Figures 3.3, 3.4, 3.5 and 3.6 are the according schedules shown. On weekends the building is unoccupied, however, some loads remain. In the office these loads are equipment (15 %) and lighting (5 %); and in the hallway lighting (5 %) and elevator (5 % traffic and 30 % standby). For the elevator schedule EnergyPlus' dataset for commercial buildings was used [58].



(a)

(b)

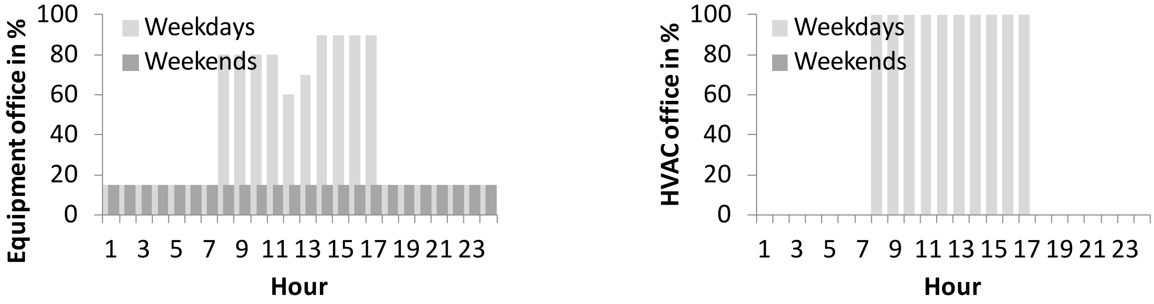
Figure 3.3: Occupation schedule of the office rooms (a) and hallway (b).



(a)

(b)

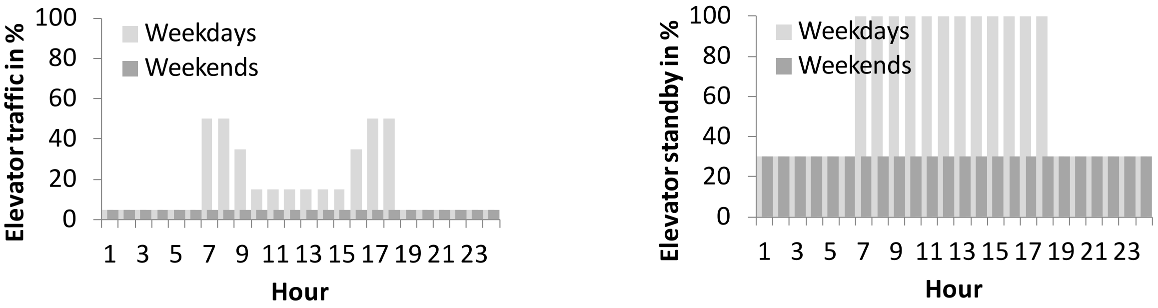
Figure 3.4: Lighting schedule for office rooms (a) and hallway (b).



(a)

(b)

Figure 3.5: Equipment schedule (a) and HVAC schedule (b).



(a) (b)

Figure 3.6: Elevator traffic schedule (a) and standby schedule (b).

3.2.2 Variable parameters

The parameters presented in this section are used for the reference models only. The improved and adapted models are using partially modified parameters which are presented explicitly where they were used.

3.2.2.1 Construction parameters

Materials and dimensions used for walls, roof and floor correspond to the most commonly ones found in literature [30], [94], [173]. The exterior walls are made of ceramic bricks with plastering on both sides and the roof is made of fiber cement tiles and slab of concrete. The absorption of the external wall corresponds to gray color with an absorption coefficient of 0.65, and the absorption of the roof is 0.70, corresponding to the color of the fiber cement tiles. The reflections of the internal surfaces are: 0.80 for ceilings, 0.50, for walls and 0.20 for floors.

Table 3.2 shows the materials used for the models and their physical properties: thermal conductivity (λ), density (ρ), specific heat coefficient (cp), thermal mass (Cth), thermal transmittance (U) and absorption (α).

Material	**Thickness in m**	**λ in W/(m K)**	**ρ in Kg/m³**	**cp in J/(kg K)**	**Cth in kJ/(m² K)**	**U in W/(m² K)**	**α**
Roof							
Ceramic roof tile	0.007	0.95	1900	840			
Air space resistance		R = 0.15			187	2.42	0.70
Concrete slab	0.080	1.75	2200	1000			
Ceiling							
Ceramic floor tile	0.019	0.14	530	900			
Concrete slab	0.150	1.75	2200	1000	59	2.21	0.80
Plaster	0.025	1.15	2000	1000			
Exterior wall							
Plaster	0.025	1.15	2500	1000			
Brick	0.014	0.90	2900	920			
Air space resistance		R = 0.16			125	2.47	0.65
Brick	0.014	0.90	2900	920			
Plaster	0.025	1.15	2500	1000			
Interior wall							
Plaster	0.025	1.15	2000	1000			
Brick	0.014	0.90	1232	920			
Air space resistance		R = 0.16			100	2.47	0.50
Brick	0.014	0.90	1232	920			
Plaster	0.025	1.15	2000	1000			
Floor							
Concrete slab	0.150	1.75	2200	1000			
Mortar	0.025	1.15	2000	1000	345	3.04	0.20
Ceramic floor tile	0.01	0.9	1600	920			
Window							
Clear glass	0.006					5.82	

Table 3.2: Physical material properties [4], [121].

3.2.2.2 Internal gains

The most common equipment present in offices are air conditioning, computers, printers, fax machines, coffee makers, refrigerators, fans, water filters, televisions and radios. The internal gain used for equipment is 9.7 W/m². The HVAC system is a split unit with a coefficient of performance (COP) of 2.8 and a set point for heating of 18 °C and of 24 °C for cooling [94], [173].

3.3 Building simulation

For the energetic building analyses mainly two computer simulation programs were used. The first one is the program Daysim, which was used for daylight simulations [141]. It is used to assess the dynamic daylight behavior and to obtain data for the lighting dimmer system. The second one is EnergyPlus, which is used for thermal energy simulations [42], [61]. It is used to obtain the final energy consumption of the models.

3.3.1 Daylight simulation

The daylight simulations were carried out using the program Daysim, which is a Radiance-based daylight analysis software. Radiance, originally developed at the Lawrence Berkeley National Laboratory (LBNL), is a validated ray tracing program that enables physical (day)lighting simulations. The simulation is based on the backward ray-tracing algorithm. As input the scene geometry, materials, light sources and sky conditions are used. Principally the direct component, specular indirect component and diffuse indirect radiation components are calculated. In addition spectral radiance, irradiance and glare indices are determined. The results may be displayed as color images, numerical values and countour plots [40].

Daysim provides data for assessing daylight and delivers hourly data for the activation of artificial lighting through an automatic control. It uses annual climate data for the building site to calculate dynamic, climate-based daylight performance metrics based on sky conditions for a full year at a given building site [141].

In order to start the simulations it was necessary to prepare the computer models in a computer aided design (CAD) program. Daysim can import models from several applications provided that the file is in 3DS format [1]. The simulation results are provided as comma separated values (CSV) file containing the artificial lighting consumption data. This data is used for calculating electricity consumption using EnergyPlus.

The lighting control system of Daysim contains a dimming control using a photoelectric sensor. It adjusts the intensity of the artificial lighting system according to the available daylight and keeps the lighting level in the environment constant. In order to determine the daylight present in the work plane, the internal environment was divided into small rectangular equally sized areas in which the averaged intensity is measured (Figure 3.7). The so formed grid of measurement points is located on a horizontal surface 0.75 m above the floor. To determine the incident lighting intensity, a photoelectric sensor was placed at all points of the measurement grid.

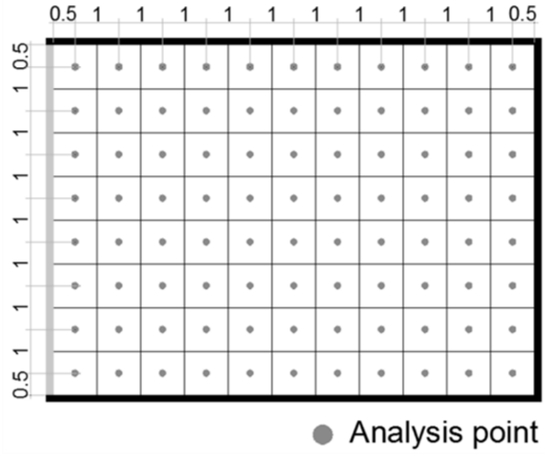


Figure 3.7: Measurement points for daylight determination.

3.3.2 Thermal simulation

Thermal energy simulations were made with the program EnergyPlus. EnergyPlus was developed as unifying successor of the two buildings simulation programs BLAST and DOE-2. It combines features from the both programs along with new capabilities. It was developed by using the heat balance based load calculation algorithm found in IBLAST[6] [169]. The core of the simulation is a model of the building based on fundamental heat balance principles [164]. The required energy (i.e. for cooling and heating) using a variety of systems and energy sources can be simulated [59].

For the models using an artificial lighting control system the data of Daysim is used as input for the thermal simulation. This is possible using the Daysim CSV file, which provides data for assessing daylight and thus delivers hourly data for the activation of the artificial lighting through an automatic control [50], [138].

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[6] The Building Loads Analysis and System Thermodynamics (BLAST) program uses heat balance methods and supports for various methods of integrating the building simulation. The three main parts of the program provide a complete simulation of a building, its fan systems and equipment. It is possible to simulate all heat transfer of each building zone due to conduction, convection and radiation, comprising infrared and visible components [169].

4 Approach towards net zero energy office buildings and its application on different building types

One of the main topics of this research and also one of the biggest subjects in sustainable build construction currently are net zero energy buildings (net ZEB). To transform buildings into ZEBs a number of measures have to be taken. Except constructive measures the new promising technology of PV windows should be examined.

As the properties of windows have a strong impact in several ways on the energy consumption of buildings, the first part of this chapter is dedicated to the influence and revenue of PV windows. Different PV window systems are tested for two Brazilian cities and compared to a city in Germany, which though the climatic conditions are not the most favorable ones for PV technology, is one of the leading countries for PV development and application. In the second part a strategy for the transformation of buildings into ZEB buildings using several constructive measures and PV technologies on the example of one representative Brazilian office model is developed. The strategy was then applied to different office building models to check on one hand the influence of the building type on the energy consumption and, on the other hand, test in general the applicability of the method. The building type analyses are shown in the third part of this chapter and in the last part the influence of a dense urban environment surrounding on the energy consumption of the building types is examined.

4.1 Performance of different window systems

Regarding the building envelope, windows are nowadays one of the main influence factors on the overall building energy consumption [14], [15], [19], [91]. However, there are many high performance fenestration products on the market today [87]. The importance of windows is based on their manifold impact on the energy consumption. Their visible transmittance influences the electric energy used for artificial lighting and their thermal transmittance greatly affects the energy consumption for cooling or heating. Beneath these two always present factors PV windows also generate energy and therefore have a third influencing factor.

As windows were identified as an important factor on the overall energetic performance of a building the behavior of different window systems was investigated. In Figure 4.1 a scheme of the process for the window performance analysis is shown. For normal window systems, i.e. not including a PV, only a daylight analysis and a thermal analysis were made. The analysis including PV windows is divided into two parts: determination of the energy consumption and calculation of the electricity generation.

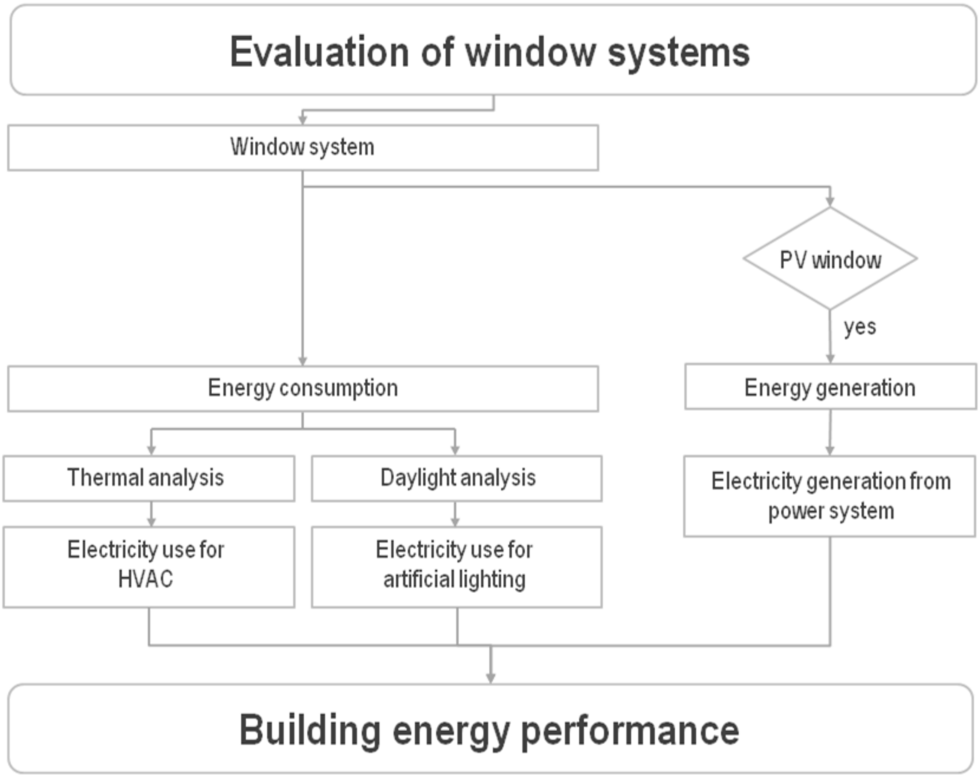


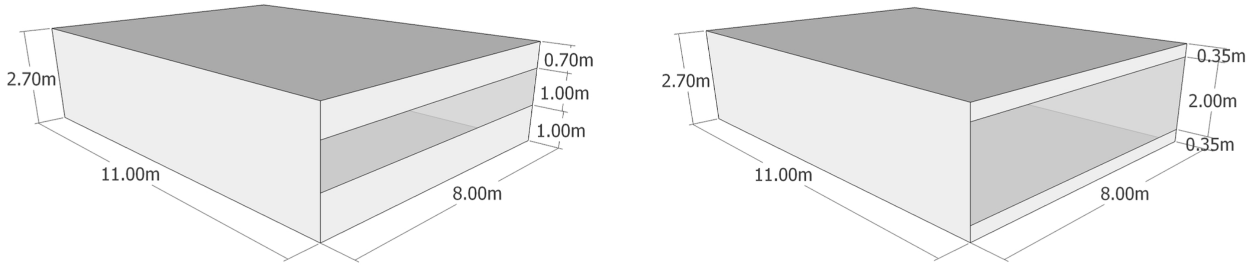
Figure 4.1: Flowchart for the determination of the building energy performance.

These analyses were carried out for the Brazilian cities Fortaleza and Florianopolis and were compared to the Germany city Frankfurt. As already explained, these cities were chosen due to their climatic differences (section 3.1). The comparison with Frankfurt is done to determine the relevance of PV windows for the Brazilian climate, since the country has high solar irradiation levels and little investments in PV technologies.

A typical office building with different window sizes was defined for the analysis. Five window types were evaluated in the office building model. Afterwards, the process for the daylight analysis and the methodology for the calculation of the generated energy by PV windows are explained in detail. Finally the procedure for a sensitivity analysis of the PV window transmittance and efficiency on the energetic building performance is described.

4.1.1 Definition of the building model

An office room representing typical Brazilian office buildings is adapted from [30], [94], [173]. For the simulations a room with a base area of 8 m x 11 m and a height of 2.7 m was used. Two different window sizes were used for the office room with different window to wall ratios (WWR) of the main facade: model W1 with a WWR < 50 %, which represents the most common window size for Brazilian office buildings and model W2 with WWR > 50 %, which represents office buildings with large windows (Figure 4.2).



(a) (b)

Figure 4.2: Scheme of the model geometry W1 (a) with a WWR < 50 % (window area = 8 m^2) and W2 (b) with a WWR > 50 % (window area = 16 m^2).

The building characteristics, materials and internal heat loads were obtained from previous studies as described in section 3.2. The internal gain from artificial lighting is 8 W/m^2, which represents an artificial lighting system with highly efficient lamps and adapted housings as it is available on the market today. In addition, an optional automatic dimming system controlling the artificial lighting was used in some of the simulations. The system turned artificial lighting on or off when daylight reached 500 lux [6]. In Table 4.1 the fixed parameters for all simulations are given.

For the reference model (base model) a single glass window was used. The artificial lighting system was switched on throughout the whole occupation period, no photoelectric sensor or dimming system and no PV window were used.

The models were evaluated for the four cardinal orientations: North (0°), East (90°), South (180°) and West (270°). The simulation regarded the building as detached and accordingly no surrounding was considered.

Thermal transmittance in W/(m² K)	Wall	2.47
	Roof	2.42
Thermal capacity in kJ/(m² K)	Wall	200
	Roof	187
Absorptance	Wall	0.65
	Roof	0.70
Average occupancy in m²/person		14.7
Internal gains in W/m²	Lighting	8.0
	Equipment	9.7
Occupation period in hour	Occupancy	8 am - 6 pm
	Lighting	8 am - 6 pm
	Equipment	8 am - 6 pm
HVAC	Type	Window unit
	Set point	18 °C - 24 °C
	Cooling capacity in BTU/h	Autosize
	COP in W/W	2.8

Table 4.1: Summary of fixed simulation parameters for the office room models.

4.1.2 Window models

For the both room models, W1 and W2, five different window systems were analyzed. The first one is a single glass window with 6 mm thickness that represents the most common window used in Brazilian office buildings [30], [94]. The other models use a double glazing insulated window (IGU) with different glazing properties (Table 4.2).

Window	**Configuration**	**U-Factor in W/(m² K)**	**VT**	**SHGC**
[A] Single glass	Clear 6 mm	5.82	0.88	0.82
[B] Double glazing	Clear 3 mm / Air 12 mm / Clear 3 mm	2.73	0.81	0.76
[C] Low-E double glazing	Low-E #2 3 mm / Air 12 mm / clear 3 mm	1.68	0.70	0.40
[D] Organic PV	Low iron 3 mm / Organic PV / Air 12 mm / Low-E #3 3 mm	1.67	0.23	0.22
[E] ASI Thru PV	Low iron 3 mm / A-SI Thru PV / Air 12 mm / Low-E #3 3 mm	1.67	0.09	0.13

Table 4.2: Windows' properties [95], [96].

All windows have a vinyl frame with an U-value of 1.70 W/(m² K). The two used PV windows and their modeling process are described in the next subsection as several programs and processing steps were necessary to integrate them into the EnergyPlus simulation. Table 4.3 describes the properties of each glass layer used for the simulations in EnergyPlus.

Glass	**Thickness in m**	**U in W/m² K**	**SHCG**	**VT**	**Solar**			**Visible**		
					Transmit.	**Front refl.**	**Back refl.**	**Transmit.**	**Front refl.**	**Back refl.**
Clear 3 mm	0.003	5.91	0.86	0.89	0.834	0.075	0.075	0.899	0.083	0.083
Clear 6 mm	0.006	5.82	0.82	0.88	0.771	0.070	0.070	0.884	0.080	0.080
Low Iron	0.003	5.91	0.84	0.99	0.843	0.134	0.134	0.993	0.003	0.003
Low-E #2	0.003	3.28	0.45	0.77	0.412	0.335	0.422	0.779	0.045	0.037
Low-E #3	0.003	5.77	0.47	0.77	0.412	0.422	0.335	0.779	0.037	0.045

Table 4.3: Glass layers' properties [95], [96].

4.1.2.1 Semi-transparent PV window

The used semi-transparent PV window consists of a double glazed window with an encapsulated solar cell layer between the glass panes. The window is composed of two glass layers with a thickness of 3 mm separated by an air filled 12 mm wide gap. The PV cell is placed at the inner side of the exterior glass. To increase the photovoltaic performance a low iron solar glass was used for the outside pane. For the interior glazing a low-E coated glass was used to prevent the heat generated by the PV from entering the building (Figure 4.3).

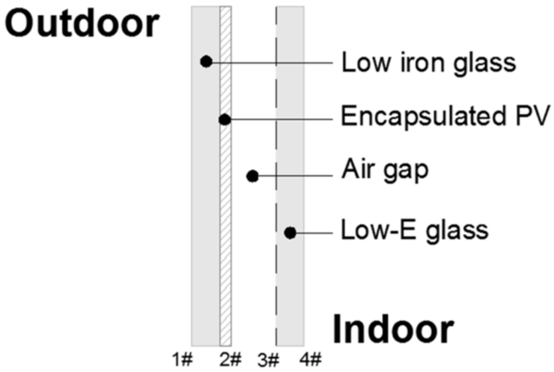


Figure 4.3: Schematic of the PV window.

Two windows with different PV solar cell types were evaluated. One organic solar cell with an efficiency of 3 % and a visible transmittance of 30 % [D] [39], [103] and a Schott ASI® thru solar cell with an efficiency of 5 % and a visible transmittance of 8 % [E] [154] (Table 4.4).

Layer	Thickness in mm	Conductivity in W/(m K)	Reflectance (β) in %	Absorption (ε) in %	Transmittance (τ) in %	Efficiency in %
Glass outside	3	1.114	8.1	1.2	90.7	-
Air gap	12	0.024	-	-	-	-
Glass inside	3	1.114	42.2	16.6	41.2	-
Organic	0.05	0.24	10.0	60.0	30.0	3.0
ASI Thru	2	0.19	12.5	79.5	8.0	5.2

Table 4.4: Semi-transparent PV windows layers properties [95], [96], [103], [154].

The encapsulated PV cell was modeled and applied to the outer glass pane as a thin film within the Optics 6 program. For this purpose the PV was modeled as an applied film. For the modeling of the film itself a file was generated with the spectral data of the PV containing the transmittance, front reflectance and back reflectance for different wavelengths. Then, the file was imported into Optics 6 where the thin film could be added to the low iron glass. Finally, the thin film covered glass was imported into the WINDOW 7 program where the window system could be modeled and simulated. Both programs are a publicly available computer programs for calculating optical and thermal performance indices of windows systems [95], [96].

4.1.3 Generated energy: semi-transparent PV window

As it is not possible to directly model a semi-transparent PV window in EnergyPlus [60] it was necessary to calculate the electricity generation of the PV cells as well as the total energy consumption separately. Another drawback of EnergyPlus is that there is no possibility to obtain temperatures inside a window [60]. This is important, as for a correct calculation of the generated electricity the PV cell temperature must be known. Hence some external heat transfer calculations were necessary to determine the PV cell temperature.

These calculations were done using the following simplifications: the window frame and temperature conduction through the window frame are not considered, neither is the heat stored inside. The glass temperature and the temperatures inside the window system are calculated for each time step of the building simulation assuming non-transient conditions for that instant of time.

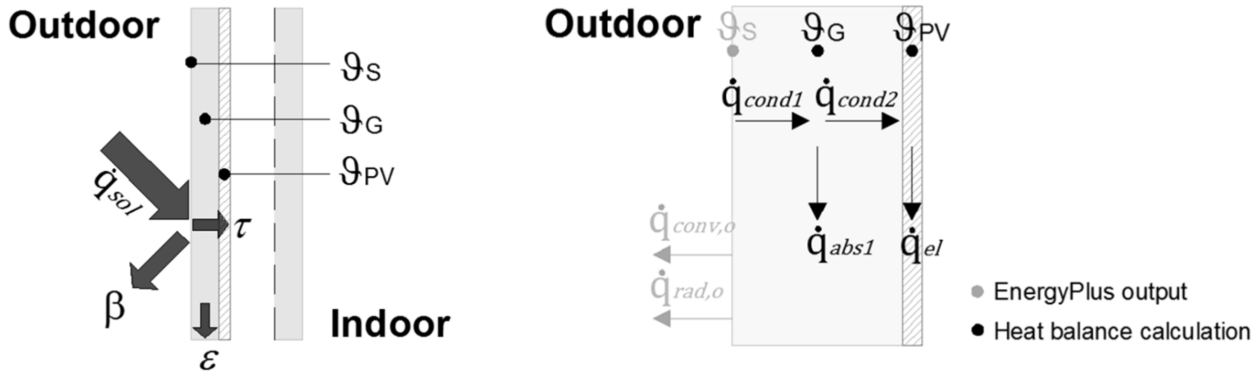
As in EnergyPlus the available daylight as well as the thermal balance should be calculated correctly the window model was adapted. A semi-transparent PV window transmits light, generates heat and electricity. But as it is not possible in EnergyPlus to consider energy generation within a window the amount of electricity generated from the incident light must be either transformed into a heat gain, transmitted light or reflected light. Transforming it into transmitted light would cause an overestimation of the available daylight inside. Increasing the absorption by the amount of the generated electricity would cause an extra heating up of the window and thus lead to an overestimation of the required cooling energy.

Therefore the generated electricity was considered as an additional reflectance of the front surface of the outside glass. Consequently, the reflection of the outside glass as it is used within EnergyPlus is calculated by equation (4.1):

$$\beta_{EP} = \beta + (1 - \beta - \varepsilon)\eta_{PV} \tag{4.1}$$

With β_{EP} reflectance used in EnergyPlus; ε , glass absorption; η_{PV}, solar cell efficiency and β glass reflection. The reason therefore is: (1 – β – ε) is the normalized fraction of light that reaches the PV and which is partly converted into electricity. The major part of the solar energy is transformed into heat, only about 3 % will generate electricity for an organic solar cell and 5.2 % for an A-SI Thru – and this fraction is added as additional reflection.

As the EnergyPlus simulation fully integrates the heat gains caused by the PV window and gives as output variables the surface temperature of the window (see also section 4.1.2.1), the convective heat transfer to the outside and the radiation heat loss to the outside, the calculation of the PV temperature is uncomplicated. Only the heat fluxes and temperatures inside the window system have to be calculated and it is only necessary to calculate the heat fluxes from one direction to the PV as the surface temperature of the outside glass already includes absorptions and heat transfers inside the window.



(a) (b)

Figure 4.4: Detailed scheme for solar radiation balance (a) and heat transfer (b).

Figure 4.4(a) shows details of the model where the incident solar radiation on the external surface is partially reflected (β), transmitted (τ) and absorbed (ε) by the outside glass pane and PV layer. In Figure 4.4(b) the locations where temperatures were calculated and the incoming and outgoing heat transfers used in the equations are shown.

To calculate the temperature of the PV layer, the temperature inside the outer glass pane has to be calculated by solving the heat balance equations below, which were based on [179]. From the heat balance of the outside glass surface, given in equation (4.2), the heat transfer into the glass pane, $\dot{q}_{cond_1}$, can be calculated.

$$\dot{q}_{conv_0} + \dot{q}_{rad_0} + \dot{q}_{cond_1} = 0 \tag{4.2}$$

With the heat transfer out of equation (4.2) the core temperature of the outside glass pane, ϑ_G, is calculated using equation (4.3), readily rewritten in equation (4.4).

$$\dot{q}_{cond_1} = \frac{1}{R_{\left(\frac{1}{2}\right)glass}} (\vartheta_G - \vartheta_S) \tag{4.3}$$

$$\vartheta_G = \dot{q}_{cond_1} R_{\left(\frac{1}{2}\right)glass} + \vartheta_S \tag{4.4}$$

The heat transfer between the outside glass pane and the encapsulated PV, node ϑ_{PV}, is determined from the heat balance of the outside glass pane, equation (4.5). To solve equation (4.5), for the temperature of the PV layer, the absorbed solar energy in the first glass pane must be calculated using equation (4.6). For the calculation of the absorbed energy the reflection and absorption coefficients of the glass are used.

$$-\dot{q}_{cond_1} + \dot{q}_{cond_2} + \dot{q}_{abs_1} = 0 \tag{4.5}$$

$$\dot{q}_{abs_1} = \dot{q}_{sol}(1 - \beta)\varepsilon \tag{4.6}$$

Finally, the searched PV temperature is calculated by equation (4.7) reformulated in equation (4.8).

$$\dot{q}_{cond_2} = \frac{1}{R_{\left(\frac{1}{2}\right)glass,\left(\frac{1}{2}\right)PV}} (\vartheta_{PV} - \vartheta_G) \tag{4.7}$$

$$\vartheta_{PV} = R_{\left(\frac{1}{2}\right)glass,\left(\frac{1}{2}\right)PV}\left(\dot{q}_{cond_1} - \dot{q}_{abs_1}\right) + \vartheta_G \tag{4.8}$$

With $\dot{q}_{\text{conv}}$ convective heat flux in W/m^2; $\dot{q}_{\text{rad}}$, radiative heat flux in W/m^2; $\dot{q}_{\text{cond}}$, conductive heat flux in W/m^2; $\dot{q}_{\text{abs}}$, absorbed heat in W/m^2; ϑ_S, outside glass surface temperature in °C; ϑ_G, outside glass temperature in °C; ϑ_{PV}, solar cell temperature in °C and R is thermal resistance in W/(m^{2}K).

The generated electricity [161] can then be calculated by multiplying the result of (4.9) by the window area. The temperature coefficient of maximum power output, K, was obtained from the PV manufacturer. The value for organic PV is +0.05 %/°C and -0.2 %/°C for ASI-Thru [131], [154]:

$$\dot{q}_{el} = \dot{q}_{sol}\,(1 - \varepsilon)(1 - \beta)\eta_{PV}[1 + K(\vartheta_{PV} - 25)] \tag{4.9}$$

With $\dot{q}_{el}$ generated electricity in W/m^2; $\dot{q}_{sol}$, solar radiation in W/m^2; ϑ_{PV}, solar cell temperature in °C; η_{PV}, solar cell efficiency; β, glass reflection; ε, glass absorption and K temperature coefficient of maximum power output.

4.1.4 Daylight analysis

The dynamic daylight results were analyzed using the Daylight Autonomy (DA) and Useful Daylight Illuminance (UDI) parameters.

4.1.4.1 Daylight Autonomy analysis

Daylight Autonomy (DA) is defined as the percentage of occupancy hours per year, for which a minimum illuminance level is reached by daylight [140]. For the analysis an illuminance of 500 lux is used [6]. A grid of equally spaced sensors was defined, which was located in a plane 0.75 m above the floor (Figure 3.7 in section 3.3.1).

4.1.4.2 Useful Daylight Illuminance analysis

Useful Daylight Illuminance (UDI) is defined as the annual occurrence of illuminances (E) that are within a predetermined range considered useful by occupants [123]. The used ranges are:

- E < 100 lux: UDI fell-short (UDI-f);
- 100 < E < 300 lux: UDI supplementary (UDI-s);

- 300 < E < 3000 lux: UDI autonomous (UDI-a)
- 3000 < E lux: UDI exceeded (UDI-e).

For the UDI analysis, the office room was divided into nine areas and the hours which attend the illuminance intervals were determined, the total of 2500 hours in the legend corresponds to the sum of occupation hours in one year. Figure 4.5 shows an exemplary result of an UDI analysis. The number written in each area is the number of hours the specified illumination level has been reached for this area throughout a year. In addition the different colors give a visual impression of the attained hour distribution inside the room.

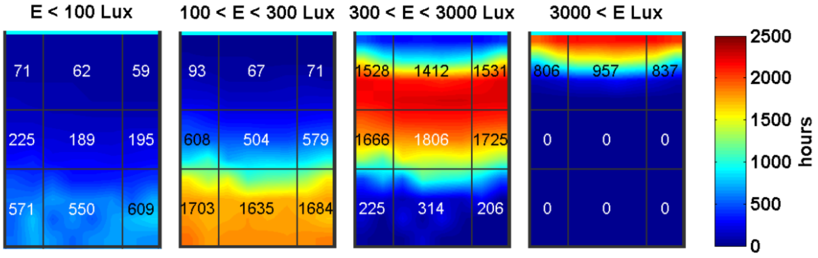


Figure 4.5: Exemplary UDI analysis, adapted from [106].

4.1.5 Sensitivity analysis

For an appropriate use of PV windows a good understanding of their two key parameters optical transmittance and efficiency is crucial. To deepen this knowledge a sensitivity analysis for the both parameters in different situations was carried out. For the sensitivity analysis different efficiencies and solar transmittances were chosen. The values are based on different semi-transparent PV technologies found in literature [32], [39], [81]. As efficiency values: 3 %, 5 %, 7 % and 9 %; and as transmittances: 0.10, 0.20, 0.25 and 0.30 were selected. Thus a total of 4 window systems is formed and 16 combinations of transmittance and efficiency have to be simulated. For the analysis the office room model W1 with a WWR < 50 % was used. Table 4.5 shows the windows' properties for different transmittances.

Semi-transparent PV window	**PV transmittance**	**U-Factor in W/(m^2 K)**	**VT**	**SHGC**
[PVA]	0.10	1.67	0.08	0.13
[PVB]	0.20	1.67	0.16	0.18
[PVC]	0.25	1.67	0.20	0.20
[PVD]	0.30	1.67	0.23	0.22

Table 4.5: Windows' properties used for the sensitivity analysis.

4.2 Strategies towards zero energy office buildings

To transform buildings into ZEBs generally a number of measures have to be taken. In this section, a strategy combining and systematizing some measures is developed. This is performed using one typical high rise building type. Afterwards the strategy is applied to other building models to check its applicability for different types.

For the assessment of the building energy consumption computer simulations using the programs Daysim and EnergyPlus, as explained in section 3.3, were used. The transformation of the building was divided into three main steps: prototype case, optimal case and zero energy case (Figure 4.6). To determine the necessary measures to progress from the prototype case to the optimal case heat balance calculations and energetic performance analyses were made. For the transformation of the optimal case to a ZEB, PV elements were added to the building, their application and sizing is described in this topic. The simulations were carried out for the Brazilian cities Florianopolis and Fortaleza.

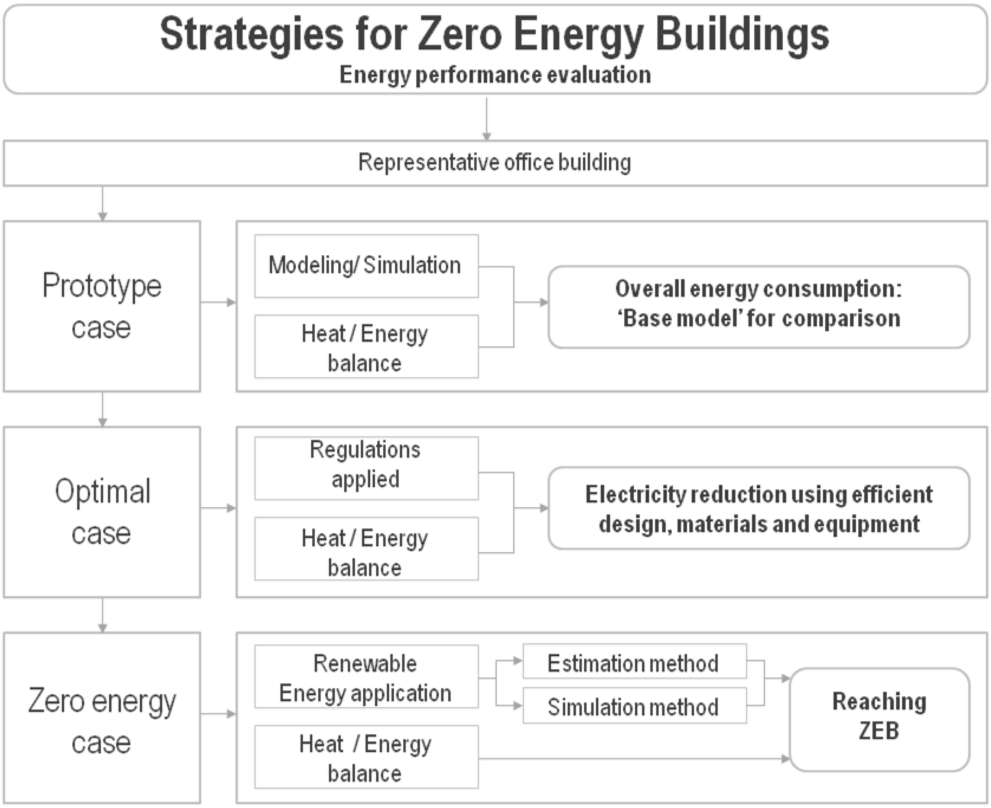
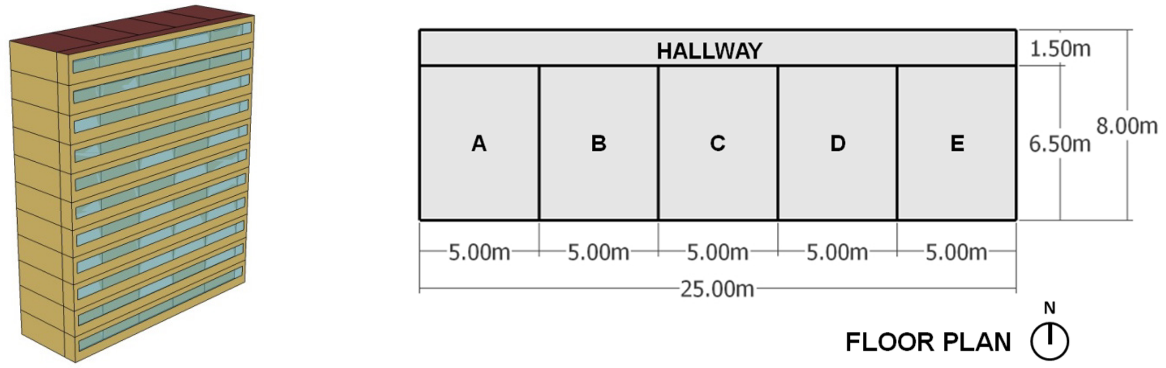


Figure 4.6: Flowchart representing the steps to reach the zero energy case.

4.2.1 Definition of the building model

A representative model for Brazilian office buildings was defined based on a literature review [30], [173]. The high rise building is composed of five office rooms and a hallway. It has 25 m x 8 m and a total height of 29.7 m. The building has eleven floors with 200 m^2 per floor and a total area of 2200 m^2 (Figure 4.7). A single clear glass is used for the windows and the WWR is 20 % for North and South facades (largest facades).



(a) (b)

Figure 4.7: Perspective view (a) and floor plan (b) of representative office building.

The building characteristics, materials and internal heat loads for the prototype case were obtained from previous studies (section 3.2). The internal gains from artificial lighting were adjusted to values proposed by ASHRAE [16]: 12 W/m^2 for office rooms and 5 W/m^2 for hallways. Elevators were considered in the simulations of the hallways to represent the conditions of vertical buildings as closely as possible. The number of required elevators was calculated according to the traffic (number of people) by [3] and the program Elevate v. 6.01 [57]. The energy consumption of the elevator for standby and traffic was calculated using the KONE Quick Energy on line calculator [92]. Table 4.6 presents a summary with the parameters used for the prototype building.

Thermal transmittance in W/(m^2 K)	Wall	2.47
	Roof	2.42
Thermal capacity in kJ/(m^2 K)	Wall	200
	Roof	187
Absorptance	Wall	0.65
	Roof	0.70
Office average occupancy in m^2/person		14.7
Hallway occupancy in persons		1
Internal gains in W/m^2	Lighting for office	12.0
	Lighting for hallway	5.0
	Equipment	9.7
	Elevator	367.5
Occupation period in hours	Occupancy	8 am - 6 pm
	Lighting	8 am - 6 pm
	Equipment	8 am - 6 pm
HVAC	Type	Window unit
	Set point	18 °C - 24 °C
	Cooling capacity in BTU/h	Autosize
	COP in W/W	2.8

Table 4.6: Parameter summary of the prototype case.

The building was oriented with the largest facades towards North and South and the hallway facing North. This arrangement was used, as it is favorable for a PV application. This is especially relevant, since the potential of PV windows should be evaluated. The building surrounding is not considered within the simulations.

4.2.2 Building analysis

For the transformation of the building the main sources for energy consumption were determined using the building's heat balance and energy balance. The calculation of either one is described in this section.

4.2.2.1 Heat balance

A heat balance calculation was performed for the whole building using outputs from EnergyPlus. The program considers heat conduction, convection and radiation between inner surfaces and the outside environment with detailed outputs for the different surfaces of the building (roof, ceiling / floor, ground floor, walls and windows). Additionally, the internal gains from infiltration, cooling, heating, lighting, people and equipment were regarded as well for the calculation [112].

The output of the thermal building simulation used for the heat balance is reported hourly. For the calculation of the heat flow through a wall EnergyPlus has a special output variable that gives the heat conduction on a surface. Using this variable has the advantage that internal gains due to radiation from other surfaces, as well as the heat flow through a wall are already considered. For windows it is possible not only to obtain the heat gain due to conduction but also the transmitted radiation [59], [60].

The result of the heat balance is the heat entering or leaving the balanced volume for the calculation period. As the heat balance is calculated using the output of the different surfaces using a spreadsheet program it is possible to easily identify the largest heat sources for an environment and thus to take efficient measures to reduce the energy consumption. The heat balance calculation can be represented by equation (4.10); where, $\dot{q}$ is the heat flux in Wh.

$$\begin{aligned} &\dot{q}_{Lights} + \dot{q}_{Equipment} + \dot{q}_{Window} + \dot{q}_{Walls} + \dot{q}_{Floor} \\ &+ \dot{q}_{Ceiling} + \dot{q}_{Infiltration} + \dot{q}_{Heating} + \dot{q}_{Cooling} = 0 \end{aligned} \tag{4.10}$$

4.2.2.2 Energy balance

The energy balance evaluates the totally consumed and produced energy in the building. EnergyPlus provides information on the final energy used by equipment, lighting, cooling, heating and fans and the energy generated by the photovoltaic panels on the roof, facade and overhangs [59], [60]. The energy generated by PV windows was calculated separately according to section 4.1.3. Therewith the energy balance is calculated by equation (4.11), where E is electric energy in kWh/mo.

$$E_{res} = E_{Equipment} + E_{Elevator} + E_{Lighting} + E_{Fans} + E_{Cooling} + E_{heating} + E_{PV} \tag{4.11}$$

4.2.3 BIPV and BAPV: applications and calculations

The reduction of the energy consumption is a necessary step in the transformation of a building to a ZEB but it is not sufficient. The used electric energy must be generated. For the on-site generation especially in urban environments PV panels are an optimal solution. Below the usable PV technologies and types are explained.

4.2.3.1 Photovoltaic technologies

Different photovoltaic technologies were chosen for the building envelope. The selected crystalline (m-Si) and thin film (CSI) solar cell technologies have the highest efficiency [41] available on the market today. The m-Si panels were placed on the roof and the CSI ones on the facade and on the overhangs. The organic (OPV) solar cell integrated into the window was selected due to its homogenous semi-transparent characteristics [39]. In addition, plastic encapsulated organic solar cells promise low production costs. However, until now this PV type is not available on the market (Table 4.7).

Manufacturer data								**Calculated**
Application	**Technology**	**Manufacturer**	**Model**	**Module area in m^2**	**Power in W**	**EFF_{STC} in %**	**k_{temp} in %/°C**	**EFF_{NOCT} in %**
Roof	m-Si	Sunpower	SPR-435-NE-WHT-D	2.16	435	20.1	-0.38	18.6
Facade/ Overhang	CIS	Solar Frontier	SF-160-S	1.2	160	13	-0.31	12.2
Window	Organic (OPV)	Laboratory	-	-	-	3	+0.05	-

Table 4.7: Characteristics of the different PV panel technologies.

4.2.3.2 Photovoltaic application

For this study all area suitable for PV application on the roof was used. A PV module coverage of 90 % for the East and West facades and 100 % for the windows in North facade and the overhangs on South facade. On the roof an inclination of 27° was used for the PV modules in Florianopolis and 3° in Fortaleza. Many references can be found in literature discussing the optimal angle for PV modules with different recommendations [44]. In this work a PV module inclination equal to the angle of the local latitude was used. Some tests with others tilts and the calculation for the PV module spacing on the roof are presented in Appendix A.1. For both cities the modules on the roof were oriented to North. On the facade and windows the PV modules were applied with a tilt of 90°, i.e. flat on the facade. On the overhangs the PV panels were applied horizontally (tilt of 0°) equal to the solar protection position.

4.2.3.3 Generated energy: estimation and simulation methods

Commonly an estimation method is used for the calculation of the generated energy. As this method is a lot easier to apply compared to a building simulation with EnergyPlus it has a great practical importance [107], [185]. To determine the accuracy of the estimation method a comparison between the two methods was carried out. One main difference between the methods is the used incident solar radiation. Thus a comparison between the solar radiation data obtained from the program Radiasol and EnergyPlus was made to better understand the differences between the energy generated using the estimation method and using the simulation with EnergyPlus. The calculation of the methods is explained below and the results of the comparison for both methods are available in Appendix A.2.

Estimation method

There are different methods to estimate the generated energy by photovoltaic modules in buildings. For this study the installed power method was used. The photovoltaic modules were distributed on the available area of the building (roof, facade and overhangs). Some space was left blank for access, cables, installation and maintenance. The number of modules was multiplied by the photovoltaic's nominal powers using equation (4.12) and the generated energy was calculated using equation (4.13) [185].

$$P_{ins} = n\, P_{nom} \tag{4.12}$$

$$W_{el} = E_{daily}/E_{STC}\; k_{eff} P_{inst} \tag{4.13}$$

Where P_{ins} is the installed power in kW, n is the number of modules and P_{nom} is the nominal power of the module in kW (for standard test conditions); W_{el} is the generated electricity in kWh/day, E_{daily} is the daily solar irradiation on the module in kWh/(m^2 day), E_{STC} is the solar irradiation for standard test conditions (1 kW/m^2) and k_{eff} is the system performance correction factor of the inverter and connections. For this study a performance of 0.85 was used as recommended in literature [185].

The daily solar irradiation for each month of the year was obtained from the program Radiasol 2 [71]. The program calculates the incident solar radiation on horizontal and inclined surfaces for all orientations, according to the provided latitude and inclination. The program generates hourly and daily radiation values.

Most PV technologies have a decreasing power output with an increasing operation temperature. This is the case for crystalline (m-Si) and the thin film (CIS) cells. For these models the corrected efficiencies (EFF_{NOCT}) were calculated according to equation (4.14).

The calculated values used for this method are presented in Table 4.7. For the simulation method, EnergyPlus does this calculus.

$$EFF_{NOCT} = EFF_{STC}\left[\frac{100 - \left(\left|k_{temp}\right| \Delta T\right)}{100}\right] \tag{4.14}$$

Where EFF_{NOCT} is the corrected efficiency for an operation temperature of 45 °C; EFF_{STC} is the normalized efficiency of the module, k_{temp} is the temperature coefficient and ΔT is the temperature difference between the standard test conditions (STC) and the NOCT operation temperature of the module. To account for an operating temperature higher than the 25 °C of the STC, a NOCT of 45 °C and thus a ΔT of 20 °C were used [126], [185].

Simulation method

EnergyPlus offers three different mathematical algorithms for the calculation of the electricity produced by a PV module. The three different algorithms are equivalent to the three objects: simple, equivalent one-diode and Sandia and differ in the prediction accuracy [60]. The simple model allows the user complete control over the PV performance, while the other two models calculate more accurately the prediction of PV operating performance [72].

For this study the simple object was used. This model is intended to be useful for design purposes to calculate the levels for annual production and peak power. EnergyPlus calculates the incident solar irradiation depending on the module inclination and orientation, considering shading and reflections.

4.3 Potential of different office building types to reach an equalized energy balance

In this section office building types with different volumetries are described to determine their potential to be zero energy, nearly zero energy or efficient buildings. Different building types were defined and converted into zero energy buildings using the methods presented in section 4.2. Figure 4.8 summarizes the steps taken.

According to the flowchart after applying the strategies for zero energy two evaluations were performed. To show energetic improvements of the buildings and examine their interaction with the electricity grid and to prove the suitability of PV technology for their application under the Brazilian climatic conditions, load matching and grid interaction indicators [147], [178] were used. To lead the limits of the different types their number of storeys was increased or decreased until they reached an equilibrated annual energy balance. Figure 4.8 summarizes the steps taken.

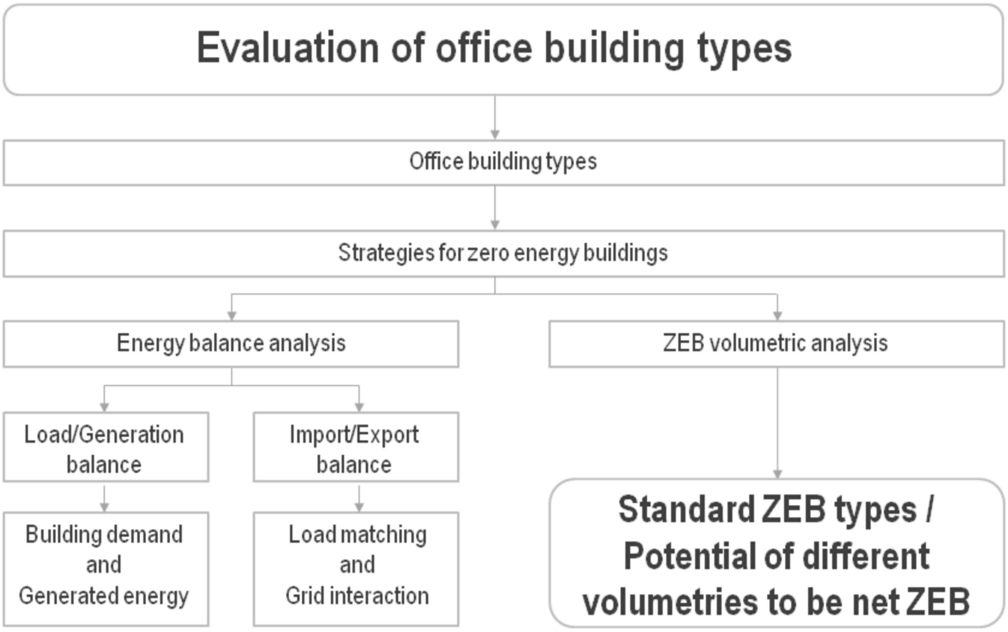


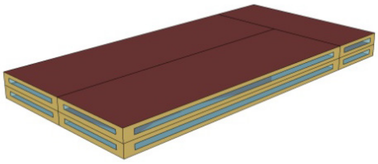
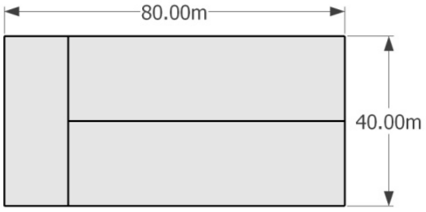
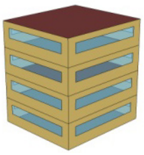
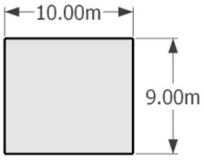
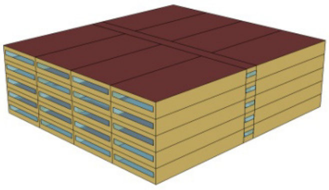
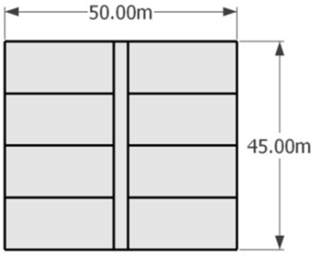
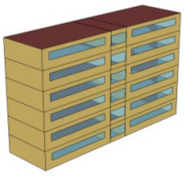
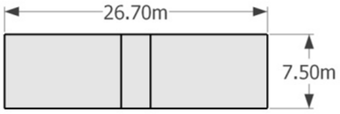
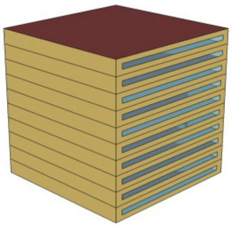
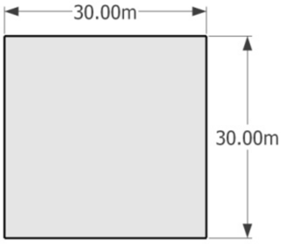
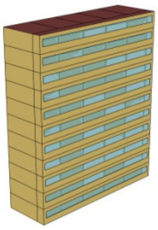
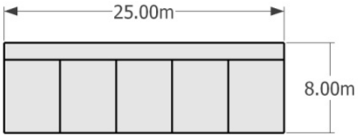
Figure 4.8: Flowchart to obtain the potential of different office building types to be ZEBs.

4.3.1 Definition of the building models

For the simulation eight representative office types were defined based on a literature review [30], [113]. To cover a wide range of the present Brazilian office buildings, types with a total built area ranging from 360 m^2 to 25,500 m^2 were considered. The types cover small, large and vertical office buildings. The models have different dimensions, heights, ceiling heights, number of floors and total area.

The used simulation parameters, building materials, devices, window to wall ratios (WWR) and internal gains (i.e. for occupancy, lighting, equipment, HVAC) are the same as used for the optimal and zero energy buildings described in section 5.2.1.

Though for an optimal use of the available solar radiation the buildings should be oriented with the largest facades to North / South in Brazil. Anyway the simulations were also made with the largest facades oriented towards East / West, as due to the buildings' environments it is not always possible to freely choose the orientation. However, for the simulations in this section, the surrounding was no considered. Table 4.8 presents the eight types, floor plans and characteristics.

Perspective view	Floor plan	Characteristics
T1		
		Dimensions in m 80 x 40 Ceiling height in m 3 Height in m 6 Total area in m^2 6400 N° of floors 2
T2		
		Dimensions in m 10 x 9 Ceiling height in m 2.7 Height in m 10.8 Total area in m^2 360 N° of floors 4
T3		
		Dimensions in m 50 x 45 Ceiling height in m 3 Height in m 15 Total area in m^2 11250 N° of floors 5
T4		
		Dimensions in m 26.7 x 7.5 Ceiling height in m 2.7 Height in m 16.2 Total area in m^2 1201.5 N° of floors 6
T5		
		Dimensions in m 30 x 30 Ceiling height in m 3 Height in m 30 Total area in m^2 9000 N° of floors 10
T6		
		Dimensions in m 25 x 8 Ceiling height in m 2.7 Height in m 29.7 Total area in m^2 2200 N° of floors 11

Continuing Table 4.8.

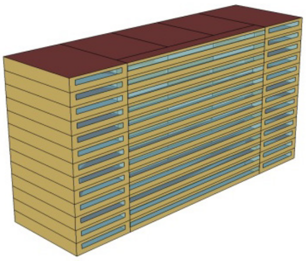
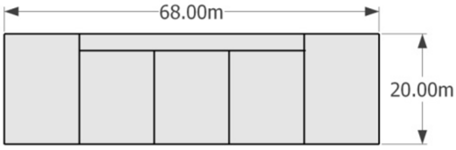
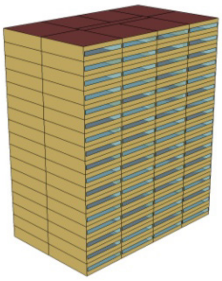
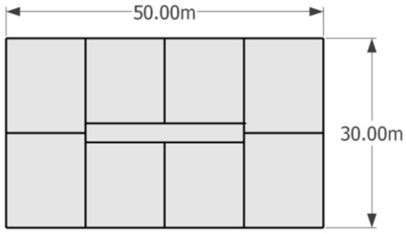
Perspective view	**Floor plan**	**Characteristics**
T7		
		Dimensions in m 68 x 20 Ceiling height in m 2.7 Height in m 35.1 Total area in m^2 17680 N° of floors 13
T8		
		Dimensions in m 50 x 30 Ceiling height in m 3.5 Height in m 59.5 Total area in m^2 25500 N° of floors 17

Table 4.8: Characteristics of the different building types.

For the simulations the thermal zones were divided into office rooms and core. The core consists of hallways, stairs, elevators and bathrooms. This zone has no air-conditioning, except for the type one (T1). The elevators were dimensioned according to the buildings' demands. Table 4.9 presents the data of the used elevators for each type.

	Building data				**Elevator data**			**Input EnergyPlus**	
Type	**Net area in m^2**	**Height in m**	**N° of people**	**N° of elevators**	**Capacity in kg**	**Traffic in kWh/y**	**Standby in kWh/y**	**Traffic in W/floor**	**Standby in W/floor**
T1	5200	6.0	354	2	450	165	2597	135.1	296.5
T2	360	10.8	24	1	450	260	2599	53.2	74.2
T3	10575	15.0	719	4	450	324	2598	212.3	237.3
T4	1067	16.2	73	1	450	348	2598	47.5	49.4
T5	9000	30.0	612	4	600	782	2620	256.2	119.6
T6	1788	29.7	122	2	450	574	2597	85.5	53.9
T7	16089	35.1	1094	6	900	1590	2670	601.0	140.7
T8	24225	59.5	1648	8	1650	4914	2953	1893.9	158.6

Table 4.9: Data of the used elevators.

4.3.1.1 Photovoltaic application

The PV modules applied on the roof, facades, solar protections and windows are the same as described in section 4.2.3.1. The installed PV power was defined according to the building's demands. Though all suitable surfaces were used, for some buildings the available surface was not sufficient to supply the required energy demand. Table 4.10 presents the applied PVs for each city, type, orientation and surface (roof, facade, solar protection and window). As explained above, the buildings were evaluated with the largest facade oriented to North-South (NS) and East-West (EW). Hence, for the same type there are different surfaces with PV application.

City	Type	Roof	Facade				Solar Protection				Window
			N	E	S	W	N	E	S	W	
Florianopolis	T1_NS	▨									
	T2_NS	▨					▨				
	T3_NS	▨	▨		▨			▨		▨	▨
	T4_NS	▨		▨		▨					
	T5_NS	▨		▨		▨	▨				
	T6_NS	▨		▨		▨					▨
	T7_NS	▨		▨		▨	▨				▨
	T8_NS	▨		▨		▨	▨				
	T1_EW	▨									
	T2_EW	▨					▨				
	T3_EW	▨		▨		▨	▨				▨
	T4_EW	▨	▨		▨						
	T5_EW	▨	▨		▨			▨		▨	▨
	T6_EW	▨	▨		▨			▨			▨
	T7_EW	▨	▨		▨			▨		▨	
	T8_EW	▨	▨		▨			▨		▨	
Fortaleza	T1_NS	▨									
	T2_NS	▨					▨				
	T3_NS	▨	▨		▨			▨		▨	▨
	T4_NS	▨		▨		▨					
	T5_NS	▨		▨		▨	▨		▨		
	T6_NS	▨		▨		▨			▨		▨
	T7_NS	▨		▨		▨	▨		▨		▨
	T8_NS	▨		▨		▨	▨		▨		
	T1_EW	▨									
	T2_EW	▨					▨				
	T3_EW	▨		▨		▨	▨		▨		▨
	T4_EW	▨	▨		▨						
	T5_EW	▨	▨		▨			▨		▨	▨
	T6_EW	▨	▨		▨			▨			▨
	T7_EW	▨	▨		▨			▨		▨	▨
	T8_EW	▨	▨		▨			▨		▨	

Table 4.10: PV application for Fortaleza, different building types, orientations and surfaces.

4.3.2 Load matching and grid interaction analysis

The energy import / export balance was analyzed using the load matching and grid interaction indices described by [147], [178]. The load matching index describes how the local energy generation coincides with the building load. It measures the degree of overlap between generation and demand profiles. In contrast, the grid interaction index specifies the energy exchange between the building and a power grid [147].

The energy exchange between net ZEBs and the grid infrastructure can be analyzed in hourly, daily, monthly and annual periods and the results for the periods may show large differences. The monthly net balance is a simplified approach for the design phase, when high-resolution profiles are not available. High-resolution simulation or monitoring is needed to describe daily and hourly fluctuations [147], [178].

Therefore, the quantitative load matching and the grid interaction indicators[7] were used. As already described, all simulated buildings use only electricity as energy source and the on-site generation is based on photovoltaic modules. The EnergyPlus output report was used to calculate the hourly, daily, monthly and annual load balance. To calculate the load match index the equation (4.15) was used [178]. Where, $f_{load,T}$ is the index in % and T is the time interval in hours (h), days (d) or months (mo). All generated power exceeding the load is considered as part of the grid electricity, so that the maximum load match index becomes 1 or 100 %.

$$f_{load,T} = min\left(1, \frac{on\ site\ generation}{load}\right) 100 \tag{4.15}$$

To calculate the grid interaction index the equation (4.16) was used [178]. Where, $f_{grid,T}$ is the index in %, T is the time interval in hours (h), days (d) or months (mo) and net grid is the energy obtained or supplied to the grid (net grid is positive for energy supplied to the grid and negative for energy obtained from the grid). Equation (4.17) shows how to calculate the standard deviation used as the annual grid interaction index.

$$f_{grid,T} = \frac{net\ grid}{max|net\ grid|} 100 \tag{4.16}$$

---

[7] There are different quantitative indicators to describe the aspects of the Net ZEBs performance [147], [178]:

- Load matching: the temporal match of the energy generation on site with the building load;
- Grid interaction: the temporal match of the energy transferred to or from a grid;
- Fuel switching: the match between the types of energy imported and exported.

$$f_{grid,year} = STD(f_{grid,T}) \tag{4.17}$$

4.3.3 Development of standard ZEB type

In this section volumetric modified versions of the office buildings described above were used to obtain a rule of thumb for standard ZEB type. The eight types described above were used as base models to derive new ones. Floors were added or subtracted from the base models until they reached zero energy buildings. PV modules were added on all available surfaces. The only surface with PV modules which remained the same is the roof. This made it possible to analyze the geometrical characteristics of ZEBs.

4.3.3.1 Photovoltaic application

For this step PV modules were applied on all available surfaces. As described in section 4.3.1.1, in Florianopolis no solar protection was needed for the South side windows, so no PV modules were applied in this place.

4.4 Influence of the urban context on the solar energy generation

The urban environment has a significant influence on the energetic performance of buildings compared to unobstructed sites [8], [125], [139], [165], [170]. The available solar irradiation in an urban environment is influenced by different urban density parameters and it has already been demonstrated that this affects the energy use for the different storeys [165]. Studies about the effect of urban design parameters (i.e. street width, density, geometrical forms and orientation) on the solar irradiation on buildings can be found in literature [33], [63], [89], [143], [165]. Figure 4.9 presents a flowchart of the applied steps.

In this section the influence of the surrounding on the PV module applicability is examined. Surroundings with different geometric properties are modeled and a method for the analysis of a building within its surrounding is presented using the computer program Diva-for-Rhino. Finally, with a detailed analysis of the available solar irradiation a strategy for the redistribution of the PV modules is developed.

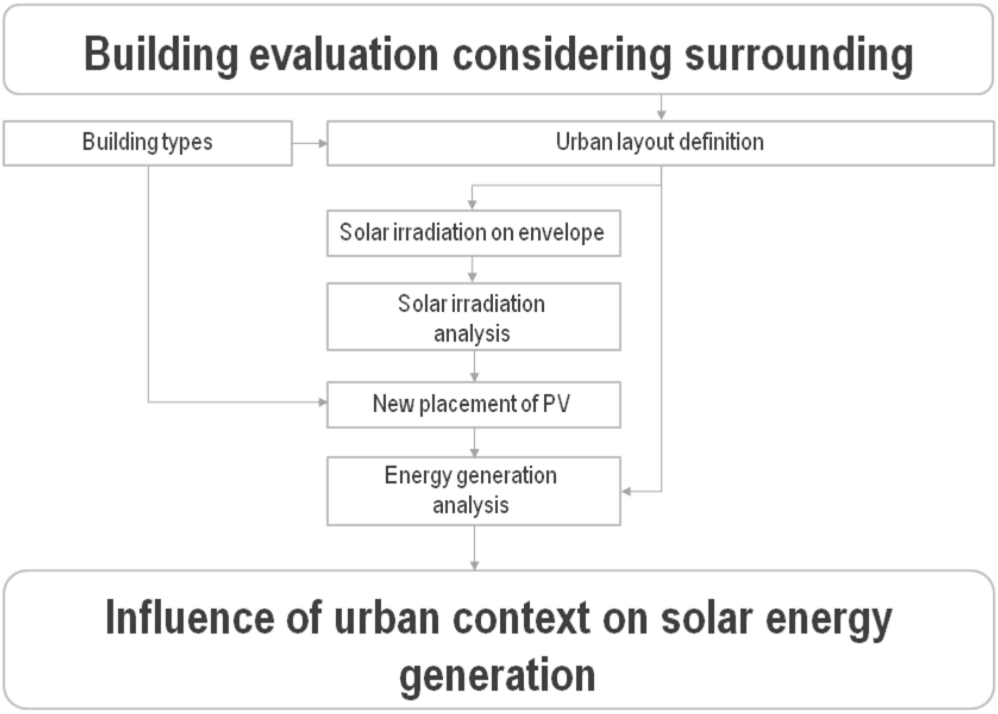


Figure 4.9: Flowchart of the urban environment influence on solar energy generation.

4.4.1 Definition of the urban layout

The models used for simulations were defined to comprise different urban scenarios. The purpose is to model various urban layouts without needing to configure a real city, thus making it possible to evaluate the performance of a building and to test the influence of different parameters.

The eight building types introduced in section 4.3.1 where analyzed in an urban context to evaluate the impact of the surrounding on the available solar irradiation. For all simulated building types a constant uniform urban plan was used. This means the urban plan and the spacing between buildings as it can be seen e.g. in Figure 4.10(a) remaind the same for all simulations of one buildings type. At the same time, two different elevation distributions were defined: a uniform one and a random one, as illustrated in Figure 4.10(b) and Figure 4.10(c). Although randomness in the urban plan is recommended for the planning of high density solar cities [33] commonly a uniform plan is used in cities today. This study intents to estimate the impact on the solar energy generation rather than realistically model urban contexts.

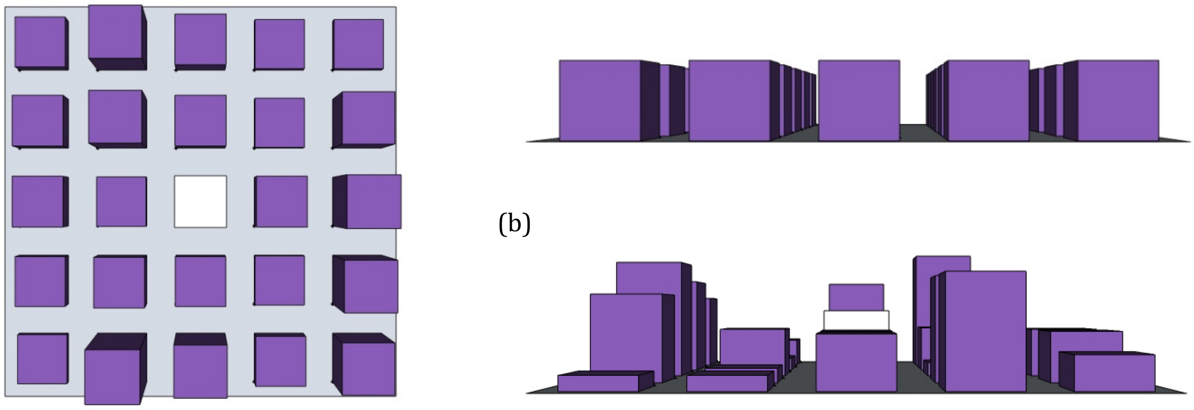

(a) (b) (c)

Figure 4.10: Urban layouts: uniform urban plan with (a) uniform elevation (b) and random elevation (c).

The urban context is represented by 25 buildings, forming a 5 x 5 mesh of regularly distributed buildings. Only the building in the center of the mesh, marked in white, is analyzed (Figure 4.10(a)). For the urban plan density, a site coverage ratio of 40 % was used. The site coverage ratio is calculated by dividing the building's footprint by its site area. The used value of 40 % was chosen according to the city planning guidelines for Florianopolis and Fortaleza [134], [135]. The plot ratio, which is defined as the ratio of a building's total floor area to the site area, is fixed for the uniform elevation layout but varies for the random elevation layout, according to building height (number of floors). The building height is one of the parameters most influencing daylight availability and solar irradiation on the facades within urban contexts [102].

Random cases

As the distribution and height of the surrounding buildings has large impact on the building performance a number of 10 different random contexts were used for each building model. The random layouts were generated using the uniformly distributed random number function of the Excel program. The heights of the surrounding buildings were determined by heights of the eight prototype models as presented in Table 4.11.

Building model	**Height in m**
1	6.0
2	13.7
3	21.4
4	29.1
5	36.9
6	44.6
7	52.3
8	60.0

Table 4.11: Buildings’ heights used for the random urban contexts.

Table 4.12 describes the 10 cases that were used for the simulation of the urban contexts for all building models, as well the heights used for the 24 surrounding buildings. The building number in column 1 of the table is equivalent to the building’s position according to the floor plan shown in Table 4.13 with the buildings' positions.

Building	**Case**									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	29.1	52.3	13.7	44.6	21.4	36.9	21.4	36.9	52.3	29.1
2	44.6	6.0	44.6	60.0	29.1	6.0	21.4	52.3	6.0	13.7
3	29.1	21.4	21.4	6.0	21.4	36.9	6.0	52.3	44.6	44.6
4	21.4	29.1	6.0	36.9	44.6	44.6	52.3	13.7	44.6	29.1
5	13.7	21.4	6.0	44.6	60.0	13.7	36.9	44.6	52.3	60.0
6	60.0	52.3	36.9	44.6	6.0	29.1	21.4	44.6	52.3	44.6
7	29.1	13.7	6.0	36.9	6.0	52.3	6.0	29.1	13.7	21.4
8	29.1	44.6	21.4	21.4	29.1	44.6	36.9	13.7	44.6	6.0
9	52.3	6.0	44.6	44.6	36.9	6.0	60.0	13.7	29.1	60.0
10	60.0	60.0	21.4	6.0	36.9	60.0	13.7	44.6	6.0	60.0
11	60.0	44.6	21.4	52.3	21.4	44.6	44.6	36.9	44.6	60.0
12	13.7	13.7	6.0	21.4	52.3	13.7	44.6	29.1	44.6	52.3
13	29.1	60.0	36.9	52.3	60.0	13.7	60.0	6.0	29.1	44.6
14	13.7	21.4	52.3	6.0	21.4	44.6	29.1	60.0	44.6	21.4
15	36.9	52.3	44.6	60.0	44.6	13.7	13.7	44.6	36.9	44.6
16	6.0	29.1	6.0	36.9	60.0	36.9	60.0	29.1	60.0	29.1
17	21.4	6.0	13.7	52.3	29.1	21.4	44.6	6.0	52.3	52.3
18	21.4	21.4	21.4	6.0	60.0	36.9	52.3	36.9	60.0	29.1
19	52.3	6.0	13.7	52.3	44.6	29.1	21.4	52.3	44.6	21.4
20	21.4	6.0	6.0	60.0	52.3	21.4	44.6	13.7	52.3	52.3
21	6.0	13.7	60.0	60.0	60.0	21.4	52.3	21.4	29.1	52.3
22	21.4	29.1	44.6	21.4	36.9	21.4	36.9	21.4	60.0	60.0
23	6.0	52.3	13.7	21.4	6.0	21.4	13.7	21.4	60.0	29.1
24	21.4	21.4	36.9	36.9	44.6	60.0	44.6	52.3	52.3	60.0

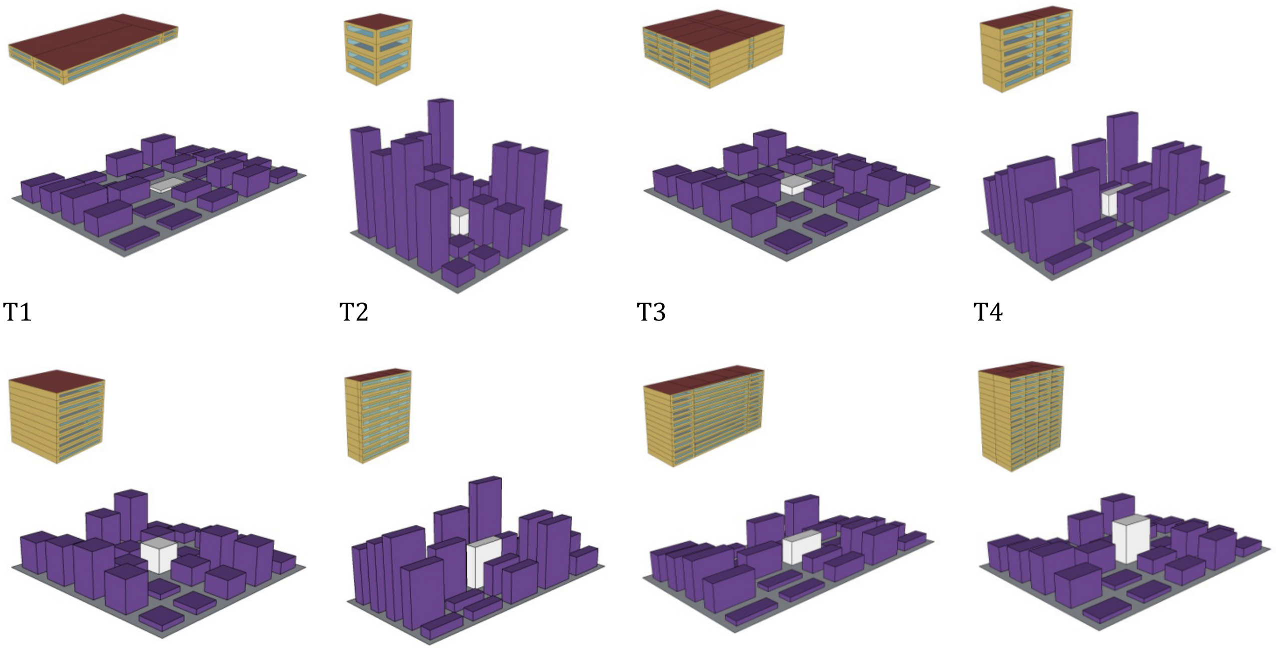
Table 4.12: Buildings' heights in m used for the random urban contexts.

1	2	3	4	5
10	9	8	7	6
11	12	**Type**	13	14
19	18	17	16	15
20	21	22	23	24

Table 4.13: Building's positions in the urban layout.

4.4.1.1 Prototypes for simulation

Using the uniformly height distribution and the 10 random height distributions described above, results in 88 urban scenarios that were modeled. In addition all theses contexts were modeled for different orientations of the largest facades of the buildings, i.e. turned to North-South and to East-West, and the two cities, Florianopolis and Fortaleza. This gives a total number of 352 simulations. Figure 4.11 presents the eight types and one example for their urban context.



T1 T2 T3 T4

T5 T6 T7 T8

Figure 4.11: Building types in an example random height urban context.

The dimensions of the building site and the urban layout for each building type were arranged and calculated using the methodology for urban energy planning developed by

[108]. It uses the building type and it is characteristics (i.e. ground floor area) to calculate the site plan for each type and consequently the city block.

Type	**Building footprint area in m²**	**Site area in m²**	**Distance between buildings in m**	**Plot ratio**
T1	3200	8000	32	0.8
T2	90	225	6	1.6
T3	2250	5625	28	2.0
T4	200	500	7	2.4
T5	900	2250	17	4.0
T6	200	500	7	4.4
T7	1360	3400	19	5.2
T8	1500	3750	22	6.8

Table 4.14: Urban contexts' parameters for a site coverage of 40 %.

Table 4.14 presents the sizes for the used site coverage of 40 %. It is noteworthy that, as the site area is fixed for each building type, the different types have different distances between buildings, which is one of the variables with the highest weight in the availability of solar radiation in urban contexts [63]. In this work, the distance between buildings is the same for all directions.

4.4.2 Simulation of the solar irradiation on the envelope

The solar irradiation on the buildings' envelopes was obtained by computer simulations with Rhinoceros and Radiance programs using the Diva-for-Rhino plug-in [52]. Diva-for-Rhino is capable to calculate several environmental performance parameters for individual buildings and urban landscapes, such as radiation maps, which show the annual irradiation at preselected node locations [85].

There are two metrics for the calculation of grid based radiation maps [52]. One is the cumulative sky method [144], which utilizes a Radiance module to create a continuous cumulative sky distribution that is then used in the radiance backward ray tracing. Another one is the daysim-based hourly metric, which was used in this work. This metric utilizes a climate-based metrics with climate data in form of *.epw files to simulate the sun and sky conditions. This annual calculation uses Radiance as calculation engine through Diva and takes the entire year into account [52].

For the simulation a three-dimensional (3D) model is necessary as input data. The 3D models were constructed by flat surfaces that represent the volumetry of the buildings and the urban context. The mesh of points was distributed uniformly on all, i.e. vertical and horizontal, surfaces of the central building, as shown in Figure 4.12. The mesh points have a separation of approximately 0.50 m. The simulation results are expressed in kWh/(m^2 y).

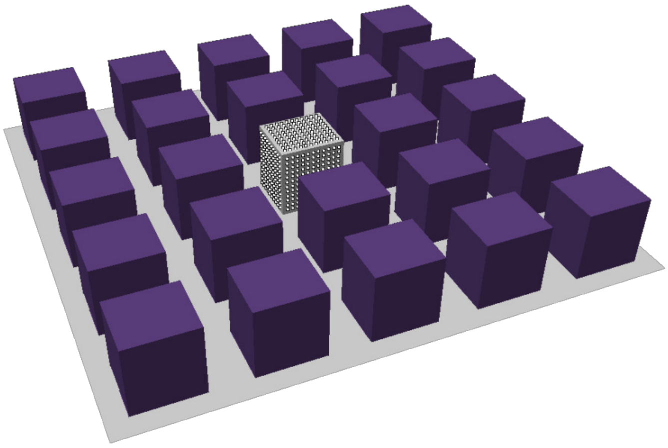


Figure 4.12: Distribution of the analysis points on the building's surfaces.

For the simulations the reflectance of the outside walls and roofs was set to 0.75, in all cases (optimal and zero energy buildings). The surfaces of the surrounding buildings have a reflectance of 0.35 and the ground of 0.20.

The simulations were carried out using the Daysim hourly based method, which runs a complete year simulation (from 01/01 to 31/12). For the Radiance parameters and geometric density the Diva default values were used.

4.4.2.1 Required solar irradiation level for PV application

To determine appropriate locations for PV panels on the envelope, a minimum solar irradiation level was defined based on economic considerations [86]. In general an amortisation period of half the life time can be considered a minimum requirement for an economic interesting investment [152].

Using a very simplified economic calculus this demand leads to the consideration that after the whole lifetime the earned founds will roughly serve to replace the worn out modules with new ones. Though such an investment this is already considered as a good investment no real revenue is generated. Therefore the amortisation period has to be shorter than half the lifetime in which case the economic benefit would really be a motivation for the installation of a PV system. The lifespan of monocrystalline PV cells is about 30 years and for thin-film modules it ranges between 20 to 25 years. Taking into account the current and prospected electricity costs and instalation costs for PV systems we can roughly estimate a meaningful minimal irradiation value for the installation of PV modules.

In Brazil PV installations cost from approximately R$ 7000 per kWp in 2013 [9], [120]. The cost of electricity depends on city and building use, however, an average for commercial buildings is R$ 0.27 per kWh [12]. Using an inflation rate of 5.2 % (average value from 2003 to 2013) [2], the energy price for the next years was calculated. Furthermore, a reduction of the PV installation costs of 60 % until 2020 was assumed for the calculations [132].

Using the installation costs of 2013 the minimal required solar irradiation level on the envelope for a PV application is 1000 kWh/(m^2 y) for a simple payback of the investment costs over a period of 15 years (Table 4.15). However, considering the 60 % reduction of installation costs until 2020 (R$ 4200) a solar irradiation of approximately 800 kWh/(m^2 y) is sufficient for a payback within 10 years, which is the value that was used in this thesis as threshold for a PV application (Table 4.16). Anyway it must be pointed out that this calculus does not consider intersts, i.e. capital costs or maintance. So to determine the profability of a real system a calculus including these factors, mainly the capital costs, has to be made.

Year / # of years	**Electricity price in R$/kWh**	**Installation price kWp in R$/m²**
		7000
		Required solar irradiation for a simple payback in kWh/m² y
2021 / 8	0.41	2332
2022 / 9	0.43	2042
2023 / 10	0.45	1806
2024 / 11	0.47	1610
2025 / 12	0.50	1445
2026 / 13	0.52	1305
2027 / 14	0.55	1183
2028 / 15	0.58	1078
2029 / 16	0.61	986
2030 / 17	0.64	905
2031 / 18	0.67	832
2032 / 19	0.71	768

Table 4.15: Required number of years for a simple payback, with investment / PV installation in 2013.

Year / # of years	**Electricity price in R\$/kWh**	**Installation price kWp in R\$/m^2**	
		7000	**4200**
		Required solar irradiation for a simple payback in kWh/m^2 y	
2028 / 8	0.59	1614	969
2029 / 9	0.62	1414	848
2030 / 10	0.65	1250	750
2031 / 11	0.68	1115	669
2032 / 12	0.72	1000	600
2033 / 13	0.75	903	542
2034 / 14	0.79	819	492
2035 / 15	0.83	746	448
2036 / 16	0.88	683	410
2037 / 17	0.92	626	376
2038 / 18	0.97	576	346
2040 / 19	1.02	531	319

Table 4.16: Required number of years for a simple payback, with investment / PV installation in 2020.

Additionally an extended lifespan of the PV panels, that can be greater than 30 years, could be considered as well – therefore a detailed economic evaluation has to be made for each case and depending on the objectives may lead to different results. Equation (4.18) can be used to determine a simple payback[8] period for a specific solar system [77]. Where T_P is the payback period; ICP is the total installed cost of the project; EAP is the estimate of annually produced electricity in kWh; and GP is the grid price per kWh.

$$T_P = \frac{ICP}{EAP\ \ GP} \tag{4.18}$$

Solar irradiation analysis

The resulting solar irradiation levels on the envelope (roof and facades) from the DIVA simulation were imported into a spreadsheet program to evaluate the solar irradiation on each surface and storey separately.

Table 4.17 shows an example on how the data was evaluated. The solar irradiation is given in kWh/(m^2 y). The columns (#0 to #10) present the urban contexts. The urban context #0 has a uniform height distribution of the buildings and #1 to #10 have random height distributions; the lines of the table correspond to the building storeys for each orientation. The cells marked show the roof and facades (storeys) average[9] solar irradiation which reached the required level of 800 kWh/(m^2 y).

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[8] A payback period is the length of time required to cover the cost of an investment [77].

[9] The average solar irradiation for each surface is calculated by the annual average of all measurement points.

Orientation/ Storey	Surface	Case										
		0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
	Roof	1630	1568	1481	1581	1515	1439	1545	1415	1596	1496	1456
North	5	973	736	635	844	790	779	581	584	888	611	832
	4	948	708	575	823	769	750	524	571	879	551	821
	3	925	627	543	802	743	672	490	557	867	519	810
	2	904	566	537	776	713	613	482	528	853	507	793
	1	881	554	529	748	683	604	475	472	839	500	781
East	5	828	609	445	568	434	440	689	439	722	591	483
	4	798	568	427	545	421	423	668	421	707	551	454
	3	755	529	411	517	399	414	627	412	691	509	441
	2	700	500	383	490	374	387	596	385	665	483	426
	1	655	471	366	459	345	370	558	370	637	460	404
South	5	423	381	394	390	321	296	366	290	393	292	313
	4	407	369	385	381	313	288	353	282	384	286	304
	3	387	351	367	365	301	276	337	271	368	275	293
	2	363	331	345	344	285	261	317	255	347	261	278
	1	331	303	315	315	260	238	290	233	317	237	254
West	5	824	627	732	763	654	428	722	407	617	477	385
	4	796	605	714	745	623	416	708	376	581	444	373
	3	753	584	684	723	573	396	679	360	545	429	354
	2	702	556	663	698	528	371	658	345	518	410	337
	1	656	529	636	671	492	344	631	327	486	390	312

Selected contexts	Solar irradiation level in kWh/(m² y)
■ Uniform and Random	▒ Roof and Facade

Table 4.17: Average solar irradiation for each storey and surface in kWh/(m² y).

4.4.3 Energy generation analysis

To calculate the generated energy and the influence of shading on the energy consumption, the program EnergyPlus was used. The influence of the surrounding on the electric energy generation was evaluated for the eight types presented in section 4.3.1 using their original PV distribution. The results are used as a basis and for a comparison to the results obtained after the reapplication of the PV modules explained in the next section.

4.4.4 New placement of PV modules

The application of PV panels is restricted by technical and economical conditions. Regarding a building without any surrounding offers the full freedom to apply PV panels in any place that seems suitable according to the buildings site and orientation. In built environments this simple approach is no longer feasible as shadowing from others obstacles has to be considered. Using the results obtained in the solar irradiation analysis the places where PV panels could be applied were redefined.

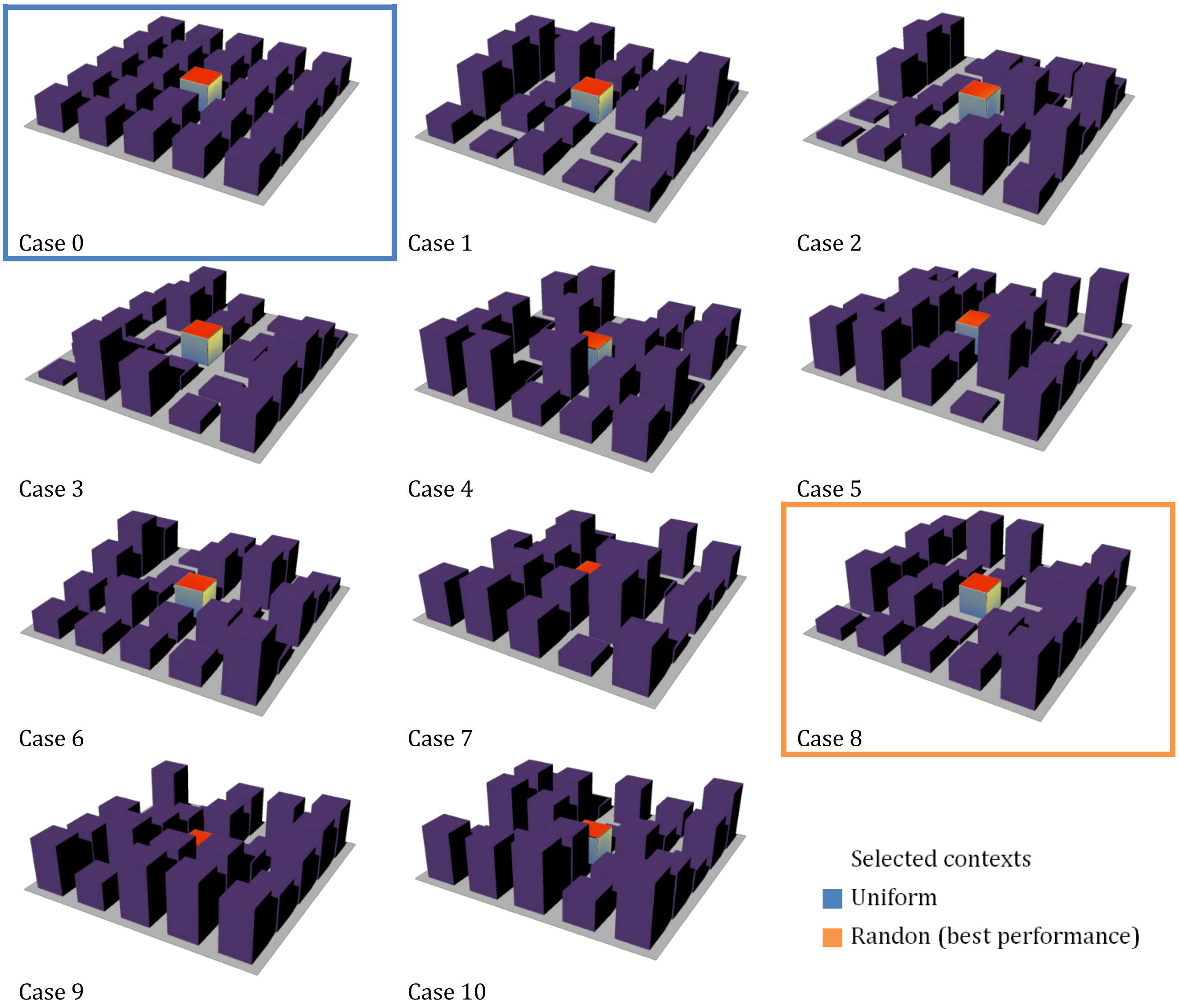


Figure 4.13: Example of selected contexts for PV re-application.

For all models with the uniform height distribution, the placement of the PV panels was redefined only according to the solar irradiation level. For the random height contexts the urban context which offered most possibilities for an application of PV modules was chosen as a basis for the re-application. The distribution given by that context was used for the application for all contexts and a second simulation. Figure 4.13 shows as an example of the 10 urban contexts for one building type. The uniform height context is market in blue and the random height urban context with the most surface (storeys) which reached the minimum level for PV application is marked in orange.

5 Results and Discussion

This chapter presents and discusses the results of the computer simulations made following the methodological steps described in previous chapters. The chapter is divided into three parts. First, the results of the simulation of different window systems including semi-transparent PV windows are analyzed. Second, the strategies and the possibilities to develop ZEB in Brazilian cities are presented. Finally, the influence of the urban surrounding on solar energy generation is shown.

5.1 Influence of different window systems on the building energy consumption

Five different window systems were evaluated related to their potential to reduce energy consumption for cooling and lighting, as well as generated electricity, in the case of semi-transparent PV windows. This section starts with a study on the energy generation of semi-transparent PV windows. Then the daylight analysis and a sensitivity analysis of the PV efficiency and the visual transmittance are shown. Afterwards a quantitative comparison of the building energy consumption for the five window systems is presented.

5.1.1 Energy generation with semi-transparent PV windows

To confirm the generated energy by the semi-transparent PV window the results obtained for the W2 office room model are presented in Figure 5.1. For all orientations the energy generation was higher for the Brazilian cities than for Frankfurt in Germany. As expected regarding the climatic data, Fortaleza achieves the highest energy generation values for both PV window types on the West facade: 798.6 kWh/y with the ASI-Thru PV and 493.6 kWh/y with organic PV.

According to the higher cell efficiency of the ASI Thru PV the highest energy generation values for the other cities were also achieved with this PV window. In Florianopolis the North facade yields the highest energy generation with 750.3 kWh/y and in Frankfurt the South facade with 591.8 kWh/y. In all cases the generated electricity of the W1 office model (window with an area of 8 m^2) is almost the half as for the W2 office (window with an area of 16 m^2).

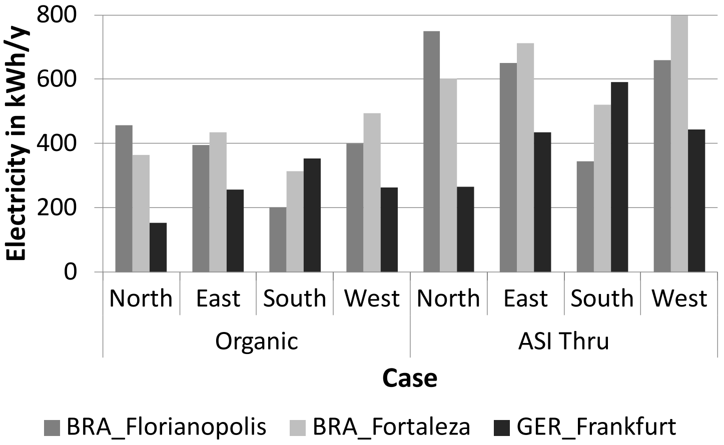


Figure 5.1: Generated energy with different semi-transparent PV windows for the W2 office room model in Brazilian and German cities.

5.1.1.1 PV temperature

The temperature of the PV window is an important issue for the application of this technology in buildings, since high temperature values increases cooling loads and might be a hazard for occupants. Figure 5.2 shows the annual course of the maximum temperature of the PV window in comparison with a conventional Low-E window and the outside air temperature. The graphics is for the West facade in Fortaleza where the highest PV temperatures using an organic PV were obtained.

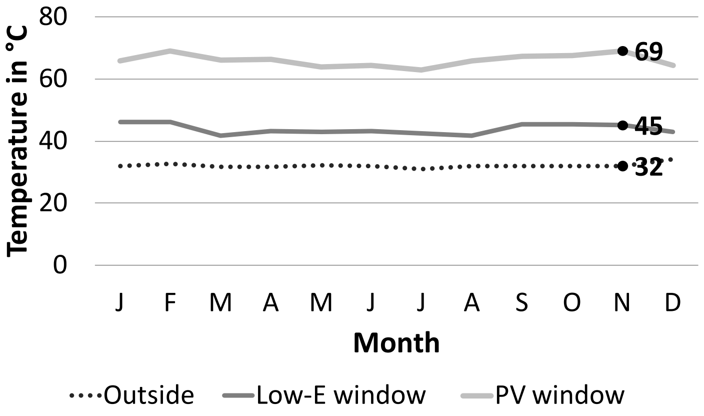
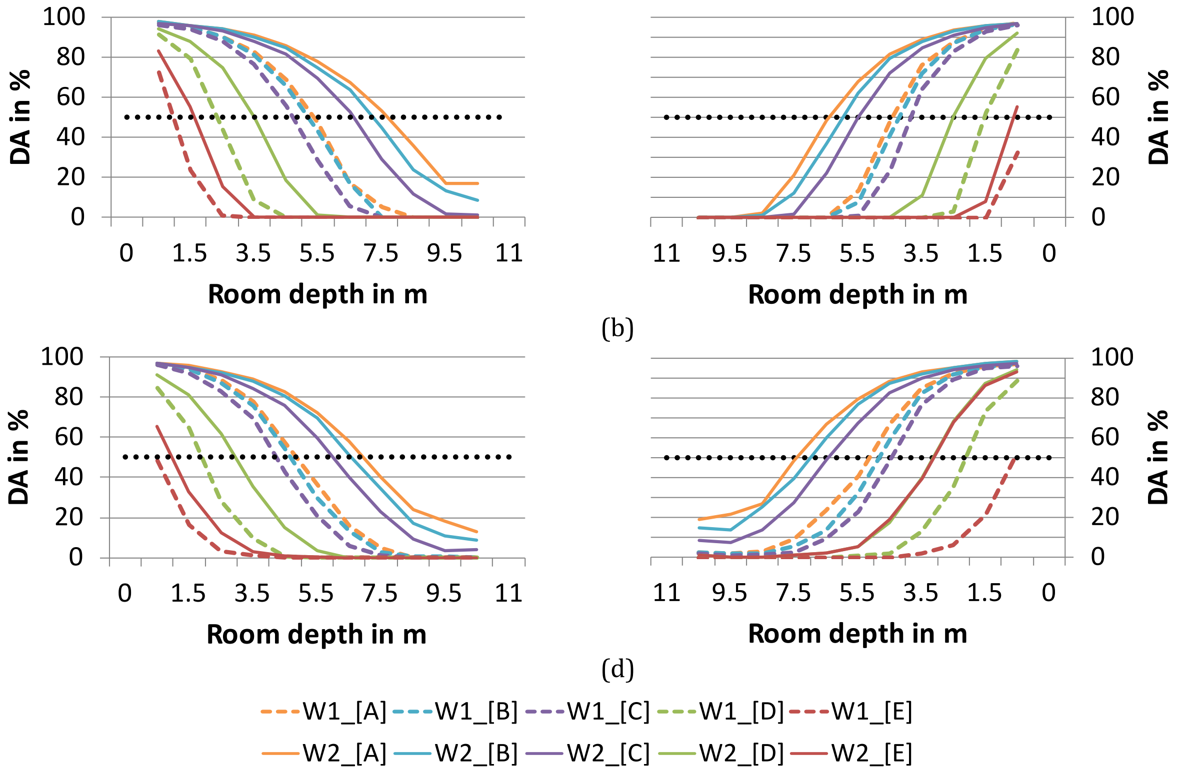


Figure 5.2: Outside air, low-E glass and organic PV temperatures for the W2 office room model for West facade in Fortaleza.

The PV temperature reaches about 69 °C in summer months, which is 35 % higher than the temperature of the Low-E window and 54 % above the outside temperature of 32 °C. When using semi-transparent PV windows in office buildings the impact of their high temperature on the thermal comfort and occupant's security have to be considered.

5.1.2 Daylighting performance

The results using the Daylight Autonomy (DA) metrics for an illuminance of 500 lux for different window systems and orientations are presented in the figures below. In Florianopolis, the illuminance near the window varies between 32 % and 98 % depending on the case. In contrast, for Fortaleza these values are between 53 % and 95 %. In Frankfurt the values are significantly lower, between 22 % and 91 %. This is caused by the latitudes of Florianopolis and Fortaleza where most daylight is available on the North facade. Using a PV window, it is possible to reach the required illuminance only near the window with WWR > 50 %: within a maximum depth of 3.5 m in Florianopolis and Fortaleza, in Frankfurt the maximum depth is 2.5 m. For a WWR < 50 % the distances decrease.



(a) (b) (c) (d)

Figure 5.3: DA (500 lux) for the North (a), South (b), East (c) and West (d) facades in Florianopolis for the different windows presented in section 4.1.2.

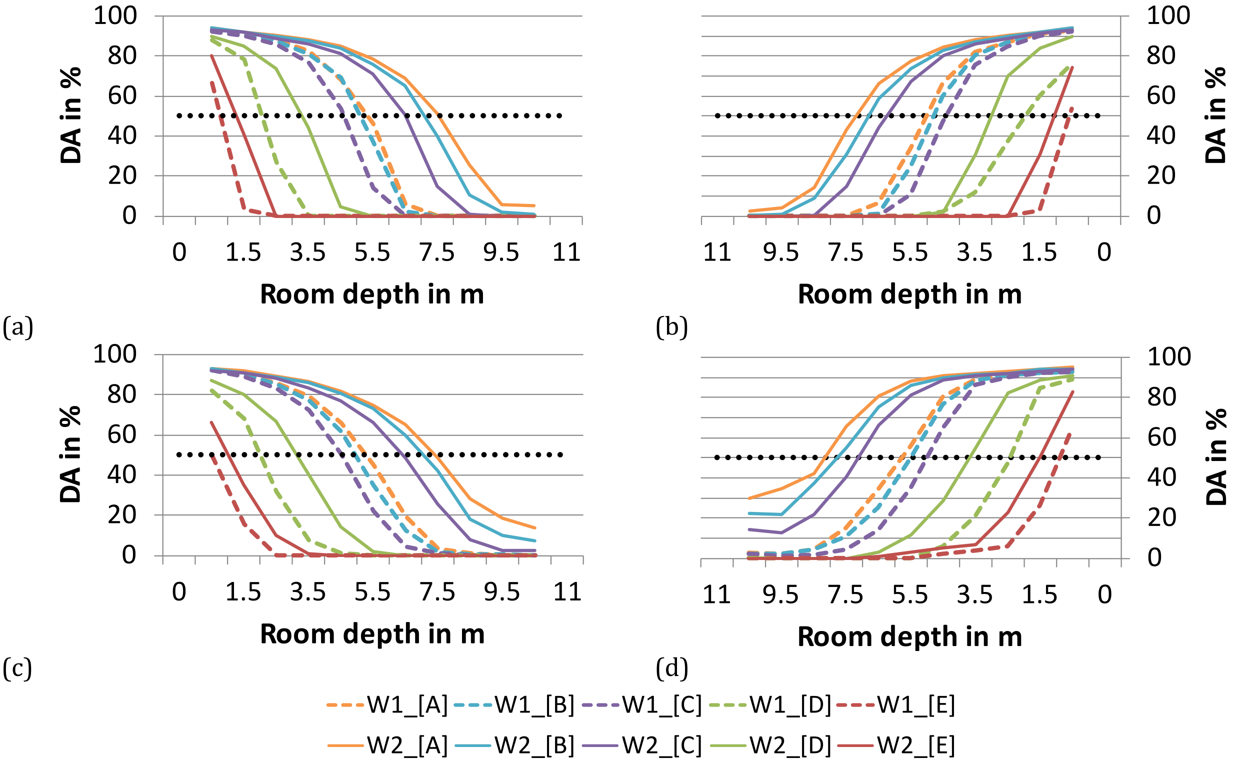


Figure 5.4: DA (500 lux) for the North (a), South (b), East (c) and West (d) facades in Fortaleza for the different windows presented in section 4.1.2.

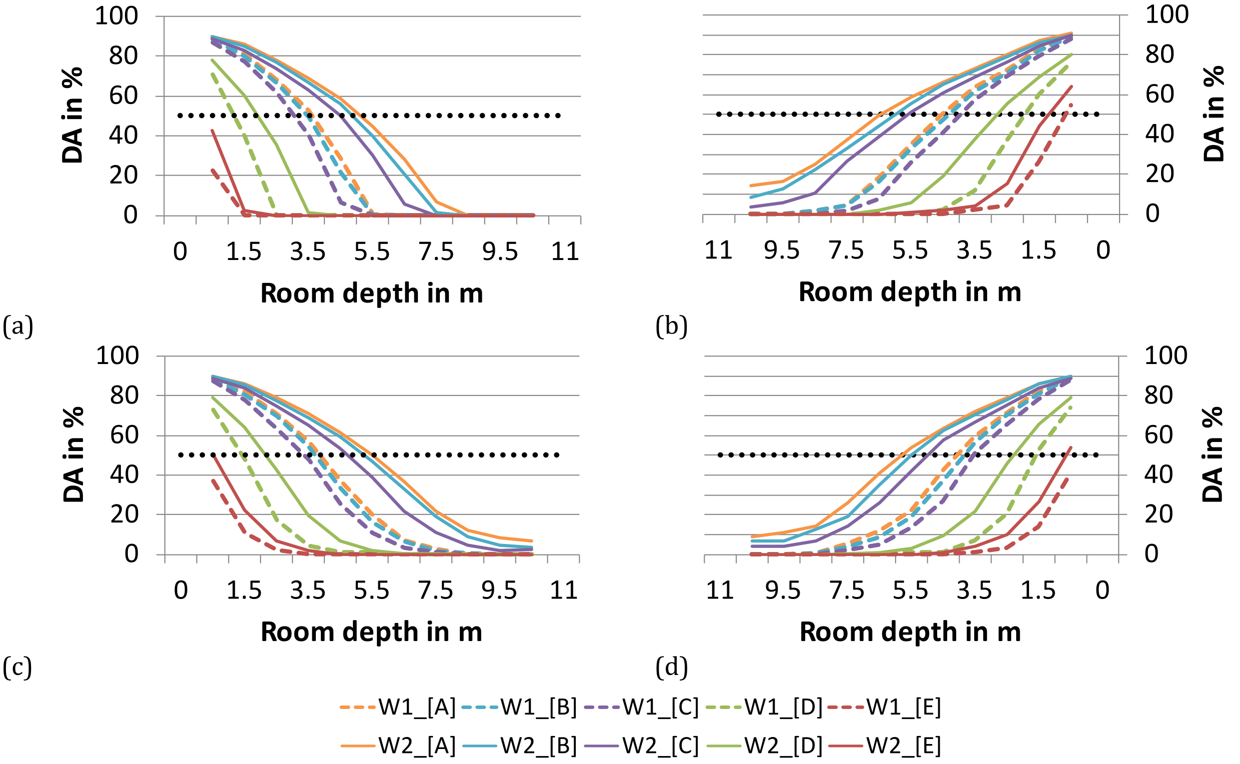
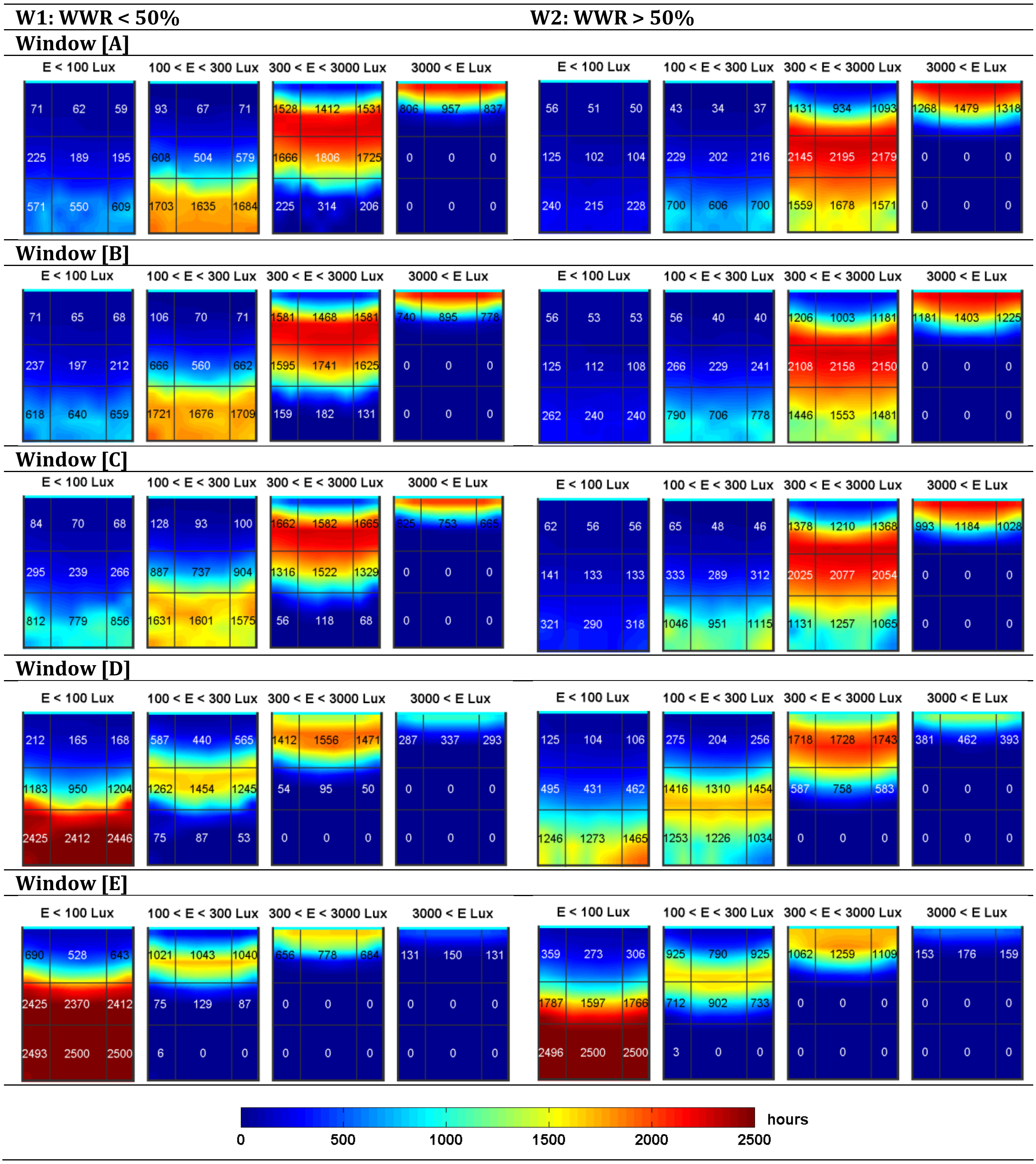


Figure 5.5: DA (500 lux) for the North (a), South (b), East (c) and West (d) facades in Frankfurt for the different windows presented in section 4.1.2.

Tables 5.1, 5.2 and 5.3 show the Useful Daylight Illuminance (UDI) results for the North facade in Florianopolis, Fortaleza and Frankfurt, respectively. The results for East, South and West facade are shown in Appendix A.3.



W1: WWR < 50% **W2: WWR > 50%**

Window [A]

E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux			E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux		
71	62	59	93	67	71	1528	1412	1531	806	957	837	56	51	50	43	34	37	1131	934	1093	1268	1479	1318
225	189	195	608	504	579	1666	1806	1725	0	0	0	125	102	104	229	202	216	2145	2195	2179	0	0	0
571	550	609	1703	1635	1684	225	314	206	0	0	0	240	215	228	700	606	700	1559	1678	1571	0	0	0

Window [B]

E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux			E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux		
71	65	68	106	70	71	1581	1468	1581	740	895	778	56	53	53	56	40	40	1206	1003	1181	1181	1403	1225
237	197	212	666	560	662	1595	1741	1625	0	0	0	125	112	108	266	229	241	2108	2158	2150	0	0	0
618	640	659	1721	1676	1709	159	182	131	0	0	0	262	240	240	790	706	778	1446	1553	1481	0	0	0

Window [C]

E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux			E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux		
84	70	68	128	93	100	1662	1582	1665	625	753	665	62	56	56	65	48	46	1378	1210	1368	993	1184	1028
295	239	266	887	737	904	1316	1522	1329	0	0	0	141	133	133	333	289	312	2025	2077	2054	0	0	0
812	779	856	1631	1601	1575	56	118	68	0	0	0	321	290	318	1046	951	1115	1131	1257	1065	0	0	0

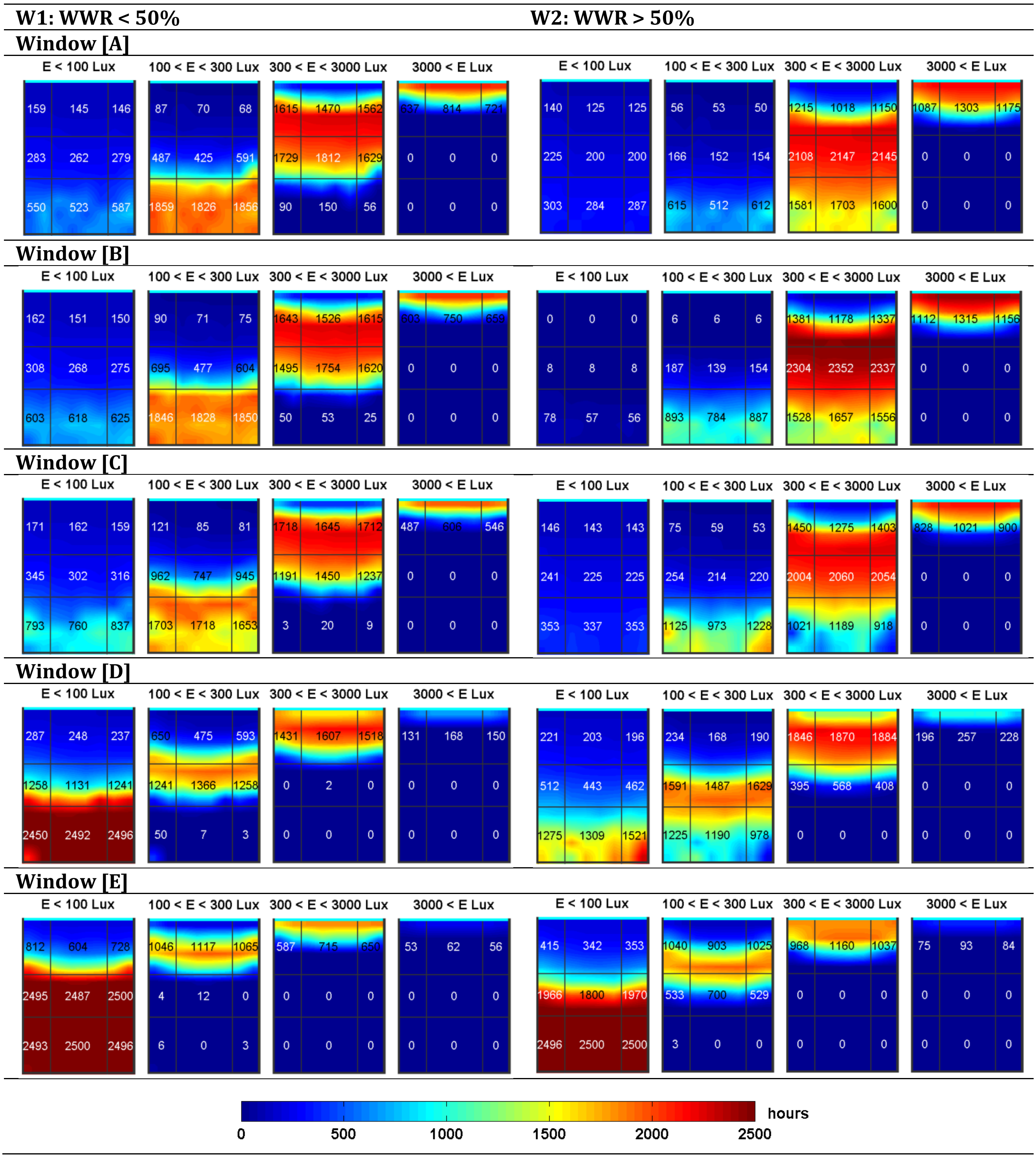
Window [D]

E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux			E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux		
212	165	168	587	440	565	1412	1556	1471	287	337	293	125	104	106	275	204	256	1718	1728	1743	381	462	393
1183	950	1204	1262	1454	1245	54	95	50	0	0	0	495	431	462	1416	1310	1454	587	758	583	0	0	0
2425	2412	2446	75	87	53	0	0	0	0	0	0	1246	1273	1465	1253	1226	1034	0	0	0	0	0	0

Window [E]

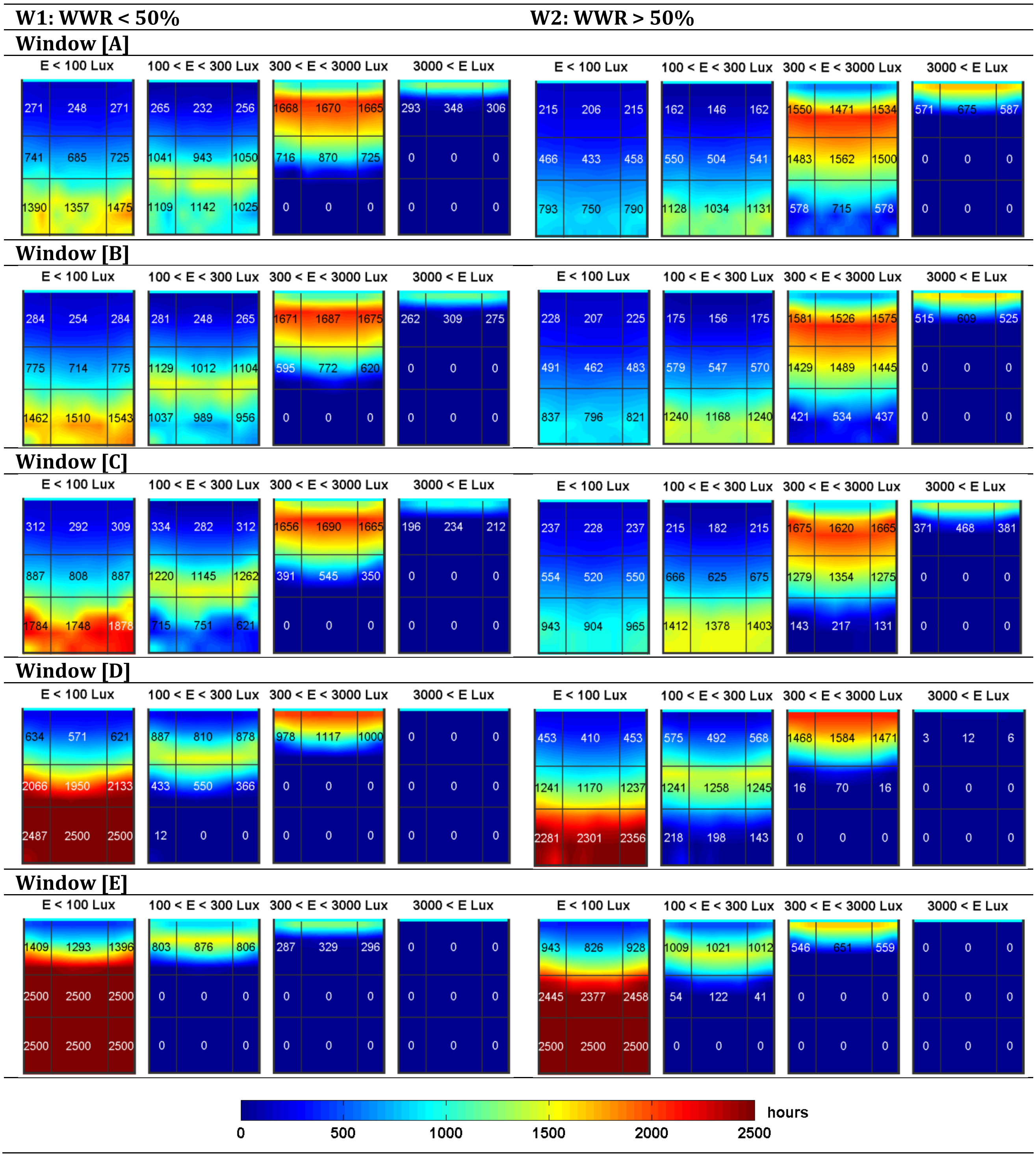
E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux			E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux		
690	528	643	1021	1043	1040	656	778	684	131	150	131	359	273	306	925	790	925	1062	1259	1109	153	176	159
2425	2370	2412	75	129	87	0	0	0	0	0	0	1787	1597	1766	712	902	733	0	0	0	0	0	0
2493	2500	2500	6	0	0	0	0	0	0	0	0	2496	2500	2500	3	0	0	0	0	0	0	0	0

Table 5.1: UDI for the North facade in Florianopolis.



W1: WWR < 50%				W2: WWR > 50%			
Window [A]							
E < 100 Lux	100 < E < 300 Lux	300 < E < 3000 Lux	3000 < E Lux	E < 100 Lux	100 < E < 300 Lux	300 < E < 3000 Lux	3000 < E Lux
159 145 146	87 70 68	1615 1470 1562	637 814 721	140 125 125	56 53 50	1215 1018 1150	1087 1303 1175
283 262 279	487 425 591	1729 1812 1629	0 0 0	225 200 200	166 152 154	2108 2147 2145	0 0 0
550 523 587	1859 1826 1856	90 150 56	0 0 0	303 284 287	615 512 612	1581 1703 1600	0 0 0
Window [B]							
E < 100 Lux	100 < E < 300 Lux	300 < E < 3000 Lux	3000 < E Lux	E < 100 Lux	100 < E < 300 Lux	300 < E < 3000 Lux	3000 < E Lux
162 151 150	90 71 75	1643 1526 1615	603 750 659	0 0 0	6 6 6	1381 1178 1337	1112 1315 1156
308 268 275	695 477 604	1495 1754 1620	0 0 0	8 8 8	187 139 154	2304 2352 2337	0 0 0
603 618 625	1846 1828 1850	50 53 25	0 0 0	78 57 56	893 784 887	1528 1657 1556	0 0 0
Window [C]							
E < 100 Lux	100 < E < 300 Lux	300 < E < 3000 Lux	3000 < E Lux	E < 100 Lux	100 < E < 300 Lux	300 < E < 3000 Lux	3000 < E Lux
171 162 159	121 85 81	1718 1645 1712	487 606 546	146 143 143	75 59 53	1450 1275 1403	828 1021 900
345 302 316	962 747 945	1191 1450 1237	0 0 0	241 225 225	254 214 220	2004 2060 2054	0 0 0
793 760 837	1703 1718 1653	3 20 9	0 0 0	353 337 353	1125 973 1228	1021 1189 918	0 0 0
Window [D]							
E < 100 Lux	100 < E < 300 Lux	300 < E < 3000 Lux	3000 < E Lux	E < 100 Lux	100 < E < 300 Lux	300 < E < 3000 Lux	3000 < E Lux
287 248 237	650 475 593	1431 1607 1518	131 168 150	221 203 196	234 168 190	1846 1870 1884	196 257 228
1258 1131 1241	1241 1366 1258	0 2 0	0 0 0	512 443 462	1591 1487 1629	395 568 408	0 0 0
2450 2492 2496	50 7 3	0 0 0	0 0 0	1275 1309 1521	1225 1190 978	0 0 0	0 0 0
Window [E]							
E < 100 Lux	100 < E < 300 Lux	300 < E < 3000 Lux	3000 < E Lux	E < 100 Lux	100 < E < 300 Lux	300 < E < 3000 Lux	3000 < E Lux
812 604 728	1046 1117 1065	587 715 650	53 62 56	415 342 353	1040 903 1025	968 1160 1037	75 93 84
2495 2487 2500	4 12 0	0 0 0	0 0 0	1966 1800 1970	533 700 529	0 0 0	0 0 0
2493 2500 2496	6 0 3	0 0 0	0 0 0	2496 2500 2500	3 0 0	0 0 0	0 0 0

Table 5.2: UDI for the North facade in Fortaleza.



Window [A]

W1: WWR < 50%				W2: WWR > 50%			
E < 100 Lux	100 < E < 300 Lux	300 < E < 3000 Lux	3000 < E Lux	E < 100 Lux	100 < E < 300 Lux	300 < E < 3000 Lux	3000 < E Lux
271 248 271	265 232 256	1668 1670 1665	293 348 306	215 206 215	162 146 162	1550 1471 1534	571 675 587
741 685 725	1041 943 1050	716 870 725	0 0 0	466 433 458	550 504 541	1483 1562 1500	0 0 0
1390 1357 1475	1109 1142 1025	0 0 0	0 0 0	793 750 790	1128 1034 1131	578 715 578	0 0 0

Window [B]

W1: WWR < 50%				W2: WWR > 50%			
E < 100 Lux	100 < E < 300 Lux	300 < E < 3000 Lux	3000 < E Lux	E < 100 Lux	100 < E < 300 Lux	300 < E < 3000 Lux	3000 < E Lux
284 254 284	281 248 265	1671 1687 1675	262 309 275	228 207 225	175 156 175	1581 1526 1575	515 609 525
775 714 775	1129 1012 1104	595 772 620	0 0 0	491 462 483	579 547 570	1429 1489 1445	0 0 0
1462 1510 1543	1037 989 956	0 0 0	0 0 0	837 796 821	1240 1168 1240	421 534 437	0 0 0

Window [C]

W1: WWR < 50%				W2: WWR > 50%			
E < 100 Lux	100 < E < 300 Lux	300 < E < 3000 Lux	3000 < E Lux	E < 100 Lux	100 < E < 300 Lux	300 < E < 3000 Lux	3000 < E Lux
312 292 309	334 282 312	1656 1690 1665	196 234 212	237 228 237	215 182 215	1675 1620 1665	371 468 381
887 808 887	1220 1145 1262	391 545 350	0 0 0	554 520 550	666 625 675	1279 1354 1275	0 0 0
1784 1748 1878	715 751 621	0 0 0	0 0 0	943 904 965	1412 1378 1403	143 217 131	0 0 0

Window [D]

W1: WWR < 50%				W2: WWR > 50%			
E < 100 Lux	100 < E < 300 Lux	300 < E < 3000 Lux	3000 < E Lux	E < 100 Lux	100 < E < 300 Lux	300 < E < 3000 Lux	3000 < E Lux
634 571 621	887 810 878	978 1117 1000	0 0 0	453 410 453	575 492 568	1468 1584 1471	3 12 6
2066 1950 2133	433 550 366	0 0 0	0 0 0	1241 1170 1237	1241 1258 1245	16 70 16	0 0 0
2487 2500 2500	12 0 0	0 0 0	0 0 0	2281 2301 2356	218 198 143	0 0 0	0 0 0

Window [E]

W1: WWR < 50%				W2: WWR > 50%			
E < 100 Lux	100 < E < 300 Lux	300 < E < 3000 Lux	3000 < E Lux	E < 100 Lux	100 < E < 300 Lux	300 < E < 3000 Lux	3000 < E Lux
1409 1293 1396	803 876 806	287 329 296	0 0 0	943 826 928	1009 1021 1012	546 651 559	0 0 0
2500 2500 2500	0 0 0	0 0 0	0 0 0	2445 2377 2458	54 122 41	0 0 0	0 0 0
2500 2500 2500	0 0 0	0 0 0	0 0 0	2500 2500 2500	0 0 0	0 0 0	0 0 0

Table 5.3: UDI for the North facade in Frankfurt.

The results show that the illuminance inside the rooms for models with a single glass [A], double glass [B] and low-E glass [C] have a similar behavior reaching the range of UDI-a (300 < E < 3000 lux) many hours per day, almost in the whole room for Florianopolis and Fortaleza and 2/3 of the room in Frankfurt. While for both PV windows (window [D] and window [E]) similar values are available only in a region close to the window (1/3 of the room).

The UDI-e (3000 < E lux) represents the highest illuminance values and it is reached in the region near the window for the models with windows [A], [B] and [C] for the Brazilian cities; and it is practically nonexistent in Frankfurt. For the PV window models the UDI-e values are considerably lower and the region where they appear is smaller. Instead the values for the UDI-f (E < 100 lux) range are higher and their distribution reaches from the middle to the bottom of the room, as expected regarding the lower visible transmittance.

5.1.3 Sensitivity analysis

The influence of the transmittance and the efficiency of the PV on the final energy consumption for the office room model W1 with a WWR < 50 % can be seen in Figures 5.6, 5.7 and 5.8 for all orientations (North, South, East and West) in Florianopolis, Fortaleza and Frankfurt. In the graphics the z-value equals the total energy consumption, the x-axis is the efficiency and the y-axis is the solar transmittance. For a better visualization and comparison the energy consumption values (z-values) were normalized with their respective maximum value.

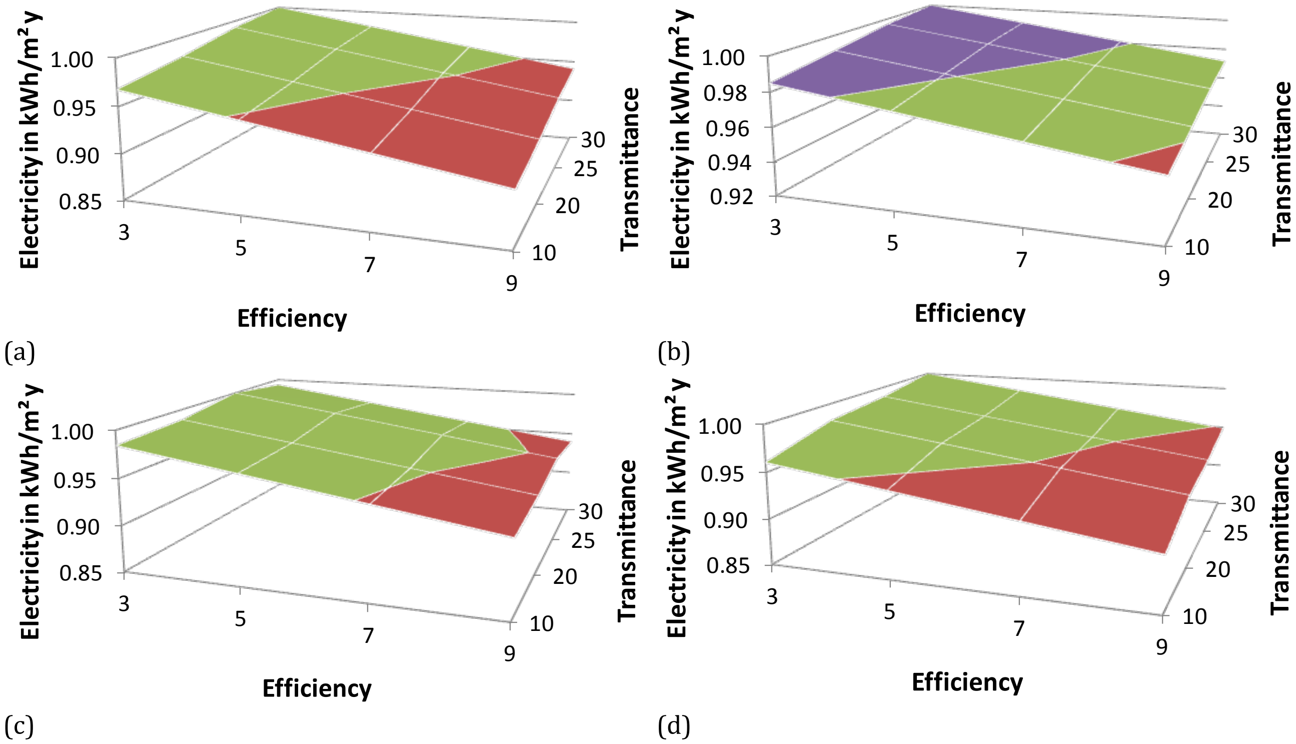


Figure 5.6: Normalized energy consumption for the W1 office room model in Florianopolis for North (a), South (b), East (c) and West (d) orientations.

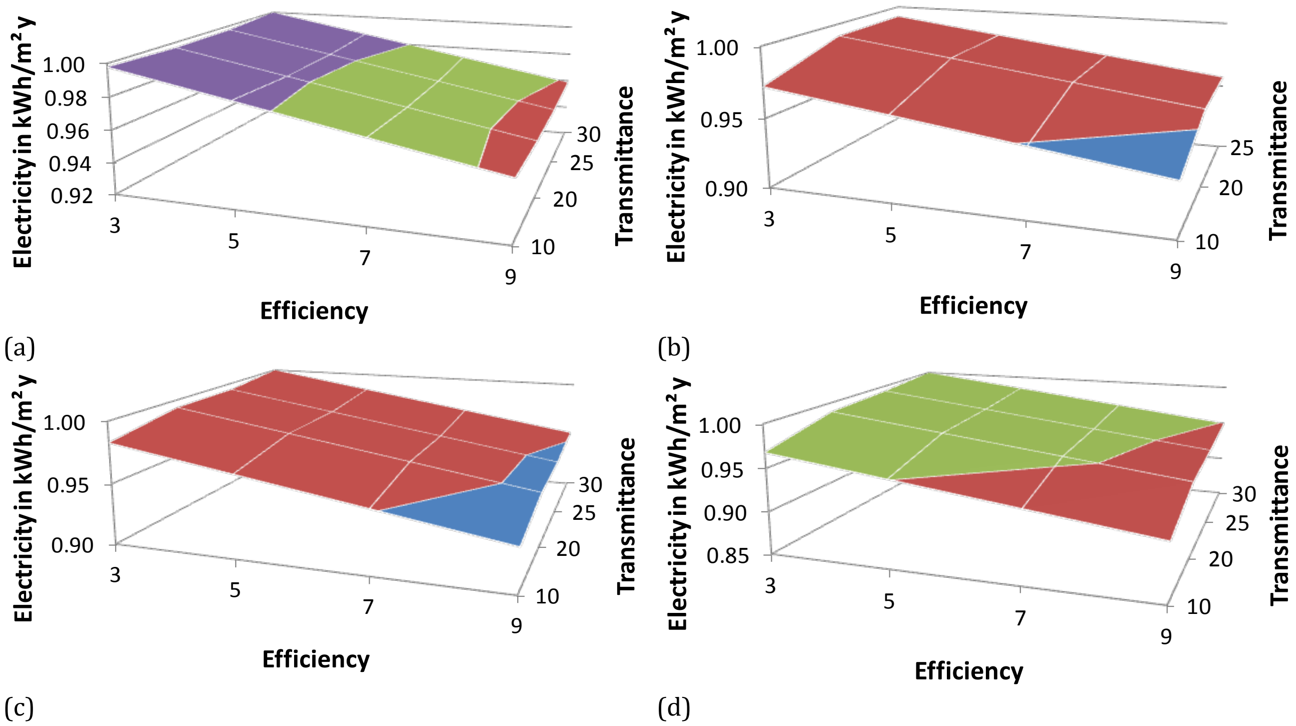


Figure 5.7: Normalized energy consumption the W1 office room model in Fortaleza for North (a), South (b), East (c) and West (d) orientations.

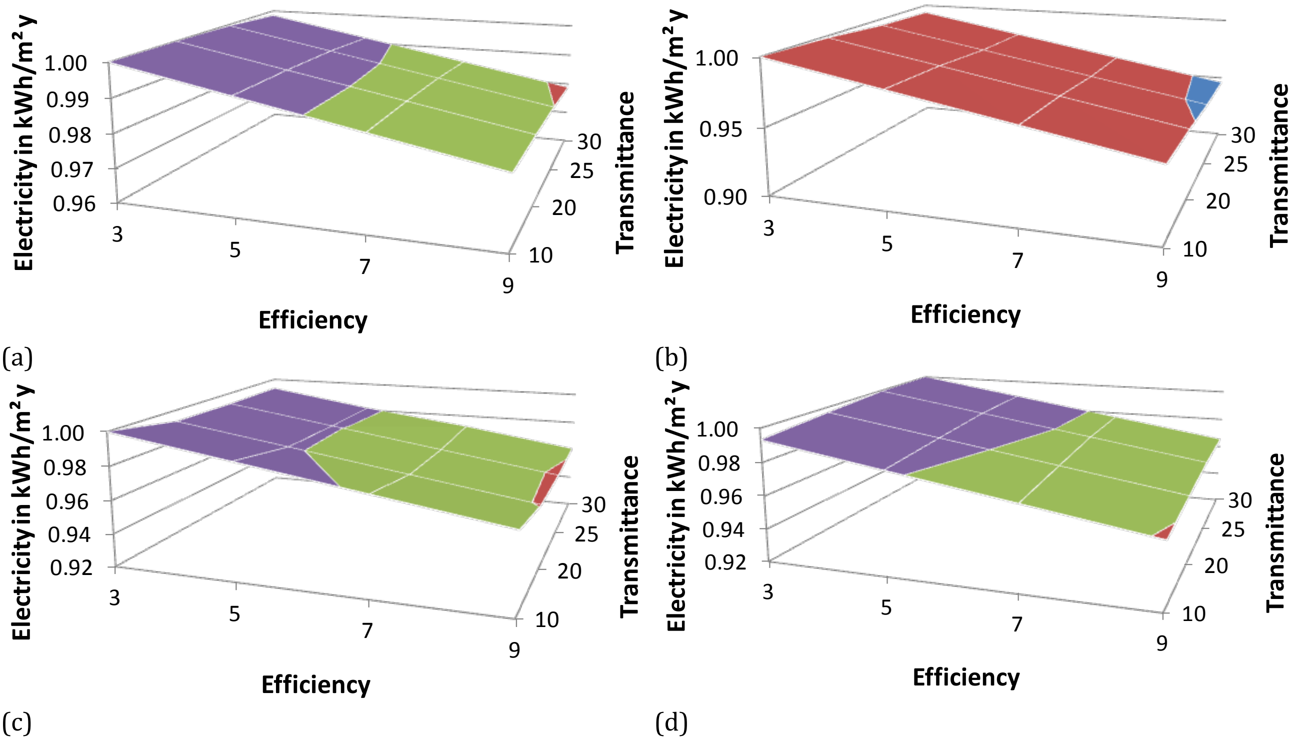


Figure 5.8: Normalized energy consumption the W1 office room model in Frankfurt for North (a), South (b), East (c) and West (d) orientations.

Table 5.4 presents the changes of the energy consumption for transmittances between 10 % and 30 % and efficiencies between 3 % and 9 %, in relation to a transmittance of 30 % and an efficiency of 3 %. Negative values indicate an increase of the total energy consumption, while positive values denote a reduction.

	Florianopolis		**Fortaleza**		**Frankfurt**	
Orientation	**Change of annual energy consumption in % compared to reference system (transmittance 30 %, efficiency 3 %)**					
	T_10 %, E_3 %	**T_30 %, E_9 %**	**T_10 %, E_3 %**	**T_30 %, E_9 %**	**T_10 %, E_3 %**	**T_30 %, E_9 %**
North	3.2	5.9	0.2	4.1	-0.2	2.0
East	0.8	5.3	1.7	4.8	-0.7	3.2
South	1.5	2.9	2.8	3.4	-0.7	4.8
West	4.0	5.1	3.2	5.1	0.7	3.5

Table 5.4: Change of energy consumption depending on solar transmittance (T) and PV efficiency (E).

For the Brazilian cities, a decreased transmittance reduces the energy consumption for all orientations. This means lower transmittances reduce the energy demand for cooling which is predominant for the overall energy consumption. The reduction of the total energy consumption due to higher cell efficiency is influenced by the available solar irradiation and accordingly different for each orientation and city. In Florianopolis the North orientation presents the highest reductions of 5.9 %, while the South orientation achieves only 2.9 %. In Fortaleza the West facade obtained a reduction of 5.1%. Only in Frankfurt the energy consumption increased for windows with low transmittance and low PV efficiency. For all studied cases, the efficiency presented a higher influence than the transmittance on the final energy consumption.

5.1.4 Building consumption

The energy consumption and generation for all cases in Florianopolis and Fortaleza are presented in Figure 5.9 . The buildings with the five window models were compared with the [Base] model (section 4.1.1) in order to analyze their energetic performance. The difference is the percentage of annual energy consumption reduction in comparison to the [Base] model, which has no lighting dimming system. As the energy consumption is calculated using particularly Brazilian building characteristics no simulations for Frankfurt were made.

The energy consumption of the installed electrical equipment is not presented in the graphics as it remained constant with a value of 3638.04 kWh/y for all cases. A heating system was integrated in the simulations but it remained unused. In Fortaleza the cooling system is required throughout the whole year and in Florianopolis the internal gains from the electrical equipment and occupants were sufficient to heat up the room in winter months.

The use of photoelectric sensors and a dimming system controlling artificial lighting according to available daylight resulted in a decrease of the consumed electricity and consequently reduced the HVAC load in all cases compared to the base model without photoelectric sensor.

The buildings have different total energy consumptions according to the facade orientation and city. In Florianopolis, a South oriented main facade has the lowest final energy consumption although the consumption caused by lighting was highest. This agrees with the expectations as it is the orientation that receives least sunlight due to its geographical location. In Fortaleza, the orientation with the lowest consumption values is North. In general, Fortaleza shows higher total energy consumption values than Florianopolis on the other side more electric energy is generated by the PV window as well. In summary Florianopolis showed a higher percental reduction of the final energy usage than Fortaleza.

The window systems caused a different energy consumption behavior of the building. The use of a PV window can save up to 43 % of energy. In some cases, the use of a low-E window saves more energy than a PV window, as for the North facade in Fortaleza with an energy saving of 37 % against 29 %. In others cases the low-E window achieved values similar to the organic PV window [D]. The single glass [A] and double glass [B] windows presented similar energy consumption values in most cases.

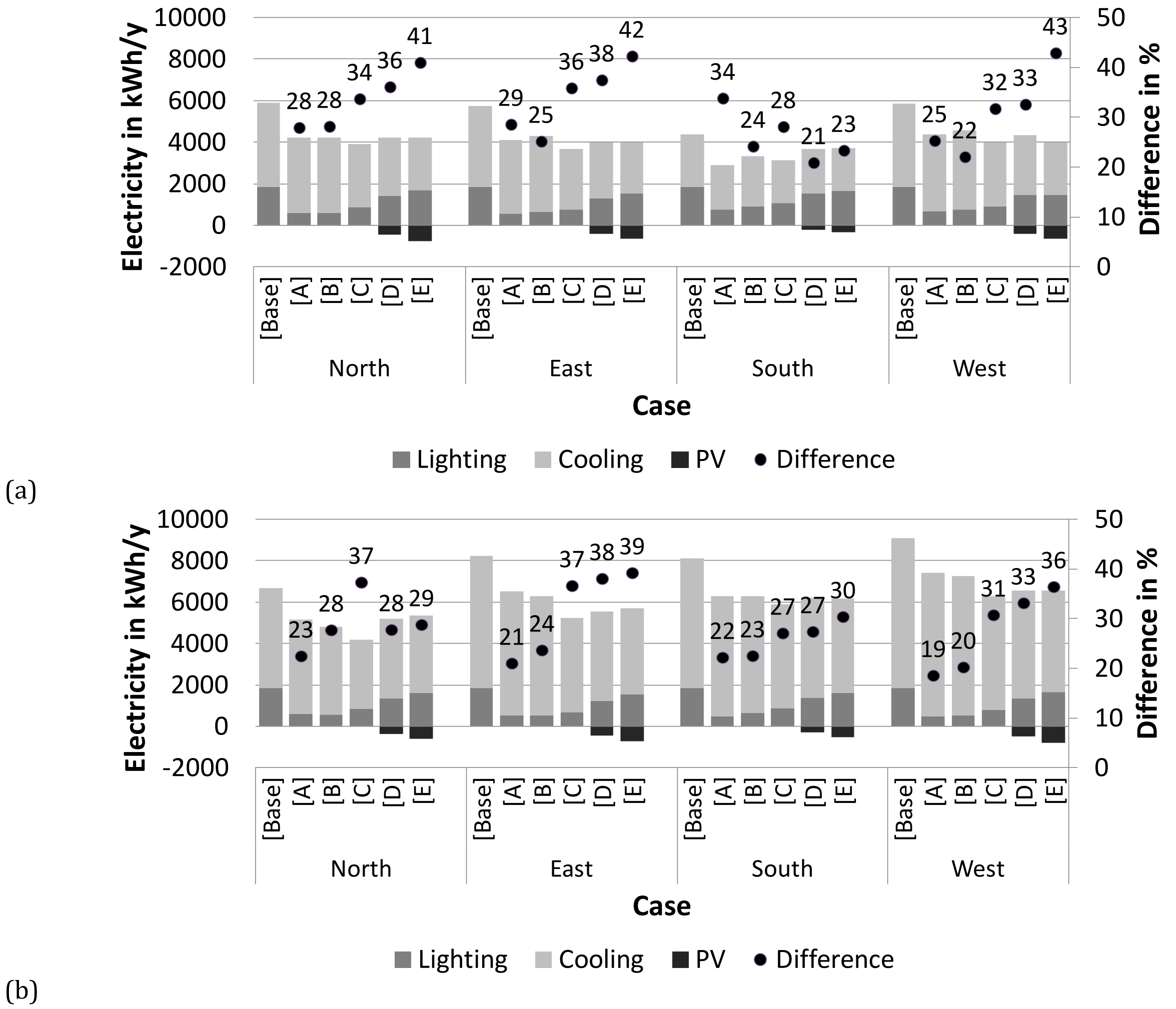


Figure 5.9: Energy consumption and reduction for the W2 office room model with different window types [A-B-C-D-E] for different orientations in Florianopolis (a) and Fortaleza (b). The difference value is the percentage of energy consumption reduction in comparison to the [Base] model.

The maximum energy reductions for HVAC achieved by the use of a semi-transparent PV window were 32 % for the East facade in Florianopolis and 30 % in Fortaleza using the ASI-Thru window. Since the PV windows have a visible transmittance of only 23 % and 9 %, respectively for the [D] and [E] cases less solar radiation enters the building and less cooling energy is required. However, due to the reduced visible transmittance the consumption for lighting increases. This could be partly compensated using the lighting control system.

Altogether, in Florianopolis the South oriented main facade has the lowest final energy consumption using a single glass window. The reasons to the low incident solar radiation levels on the facade which cause low cooling loads, in combination with a good light supply using the highly transparent single glass window.

Figure 5.10 shows that, comparing the PV windows [D] and [E] with the single glass window [A], the PV windows always require more artificial lighting to reach 500 lux in the work plane. Besides this for the building with the smaller window the energy consumption for artificial lighting increases more than for the building with the bigger window, due to the energy generated by PV modules. Comparing the single glass window with both PV windows the energy consumption increased between 18 % to 45 % for the organic PV window and 12 % to 44 % for the ASI Thru window in Florianopolis and 15 % to 53 % and 14 % to 55 %, respectively in Fortaleza.

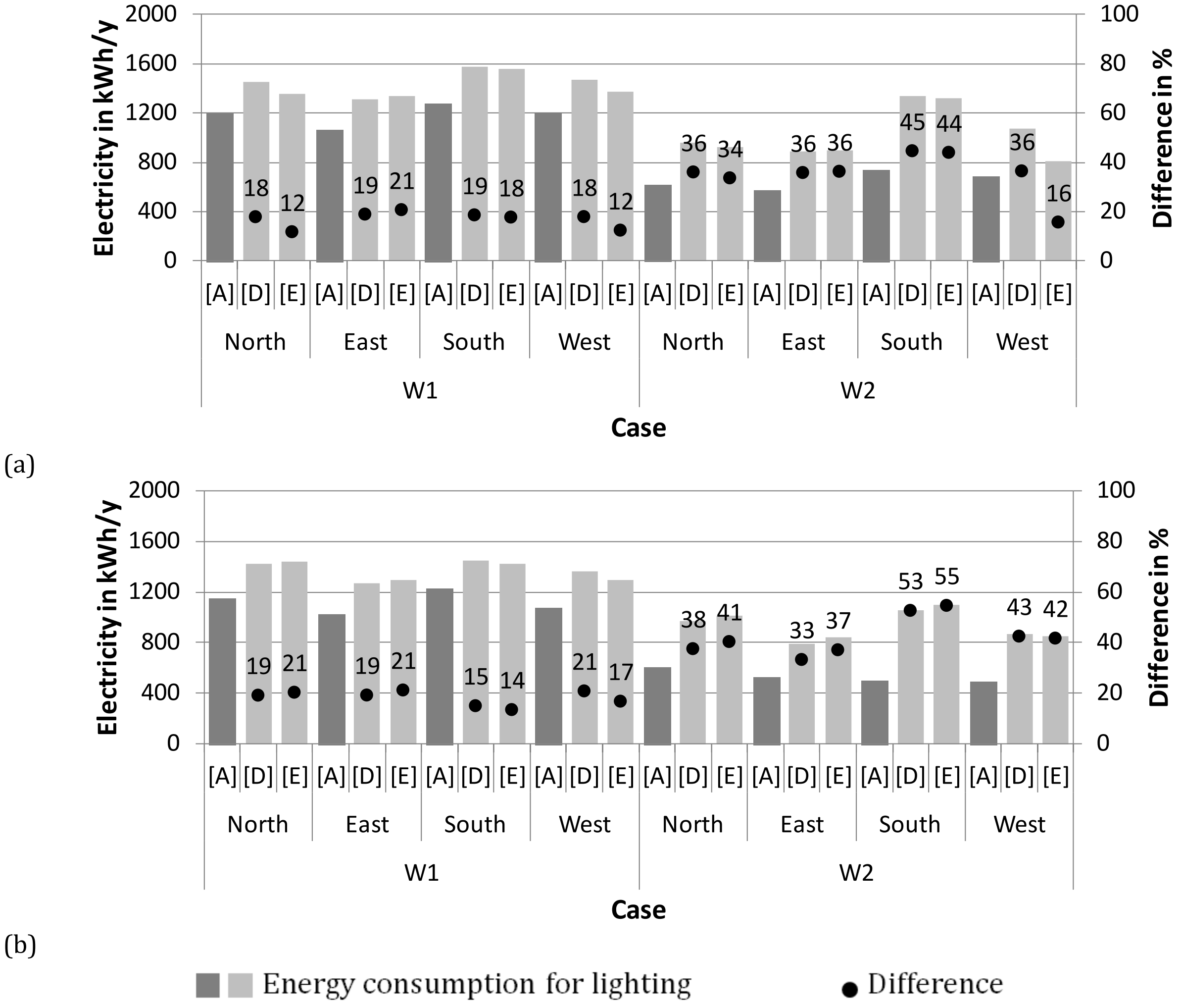


Figure 5.10: Energy balance between artificial lighting energy use and PV window electricity generation for W1 and W2 office room models in Florianopolis (a) and Fortaleza (b). The difference value is the percentage of the annual electricity consumption in comparison to the model [A].

Figure 5.11 shows the influence of the window size on the overall energy consumption for the W1 and W2 case for the North facade in Florianopolis. The window with a WWR < 50 % has a higher consumption for lighting since less daylight enters the building, compared to a WWR > 50 %. In contrast the building with the bigger window requires more cooling energy as more heat reaches the inside. For a WWR < 50 % the windows without PV have a lower total energy consumption than the PV windows. In contrast for a WWR > 50 % the PV windows use less energy, mainly due to two times higher energy generation.

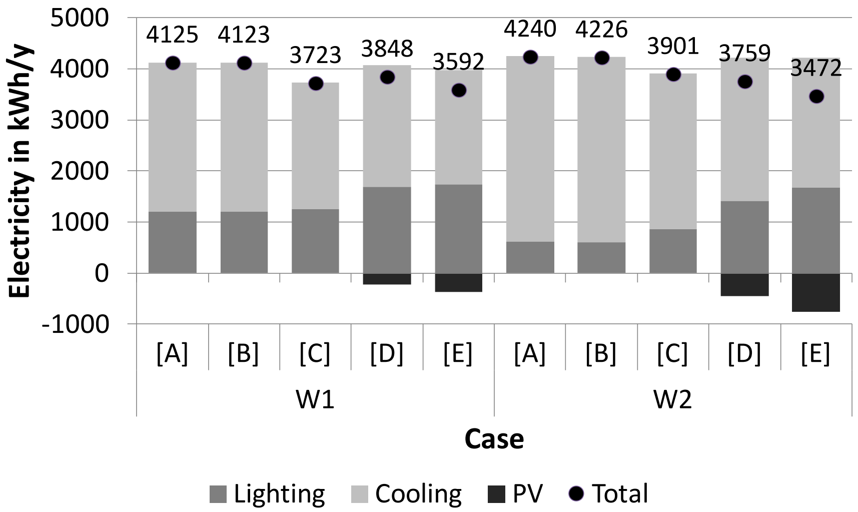


Figure 5.11: Energy consumption for W1 and W2 office room models with different window types for the North facade in Florianopolis. The total value is the final electricity consumption summing up energy consumption and generated energy.

A summary of the windows' performance in relation to the total consumed energy is presented in Table 5.5. For the classification, the number 5 represents the best performance (low energy consumption) and number 1 the worst performance (high energy consumption).

		Window				
City	**Orientation**	**[A] single glazing window**	**[B] double glazing window**	**[C] low-E window**	**[D] organic PV window**	**[E] ASI Thru window**
Florianopolis	North	1-2	1-2	3	4	5
	East	2	1	3	4	5
	South	5	2	4	1	3
	West	2	1	3-4	3-4	5
Fortaleza	North	1	3	5	2	4
	East	1	2	3-4	3-4	5
	South	1	2	3-4	3-4	5
	West	1	2	3	4	5

Table 5.5: Classification of the windows' performance by city and orientation.

5.1.5 Summary of the analysis

The results show a considerable potential for solar energy generation in the two Brazilian cities Fortaleza and Florianopolis. In Fortaleza more energy was generated than in Florianopolis, however, the reduction of the total energy usage is higher in Florianopolis than in Fortaleza.

There is no window type that performs best in all conditions. The single glass window, which is the most commonly used window type in Brazilian office buildings, showed similar values as the double glass window. The low-E window presented the best overall performance for the South facade in Florianopolis and the North facade in Fortaleza, which are the facades that receive least solar radiation. For the other facades the PV window presented the overall best energetic performance.

The sensitivity analysis revealed that transmittance and PV efficiency are linear independent for the overall energy consumption thus the both factors can be examined independent of each. For all cases, the efficiency has a higher influence on the final energy consumption than the transmittance. The actual influence of the transmittance is depending on the climate and the orientation and cannot be predicted in a simple manner. For the determination of the optimal transmittance a simulation should be carried out.

The PV window technology is an appropriate choice for environments with air conditioning or environments with low light demands. For example corridors and hotel rooms where since the use of the PV windows in conjunction with dimmer and light sensors that control artificial lighting efficiently, they can reduce the total electricity consumption.

In conclusion, the PV window technology is not applicable for all orientations and cities (e.g. South facade in Florianopolis), the local climatic conditions, especially the available daylight and temperature have to be considered carefully. For the use of PV windows in environments that do not require artificial cooling, a study using different transmittances and efficiencies is recommended.

Although semi-transparent PV windows with ASI thru cells result in a higher reduction of the required cooling energy due to their low visible transmittance, the window with organic cells is preferable because of their better daylight supply inside the room, as it also can be seen in the analyses. In addition, it is considered that a visible transmittance of 25 % is the benchmark for window application [32]. Therefore the latter one was chosen for further simulations.

5.2 Reaching zero energy office buildings

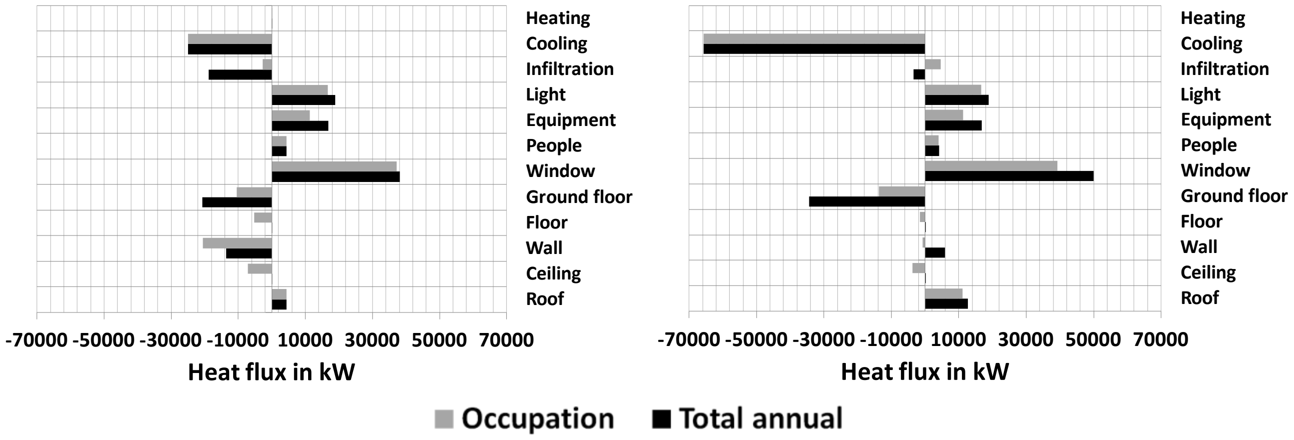
This section focuses on the transformation of conventional office buildings into (net) zero energy buildings. It is divided into five main parts. The first part demonstrates the transformation of the prototype building initially into an energy-efficient building, which will be called optimal case and then into a zero energy building. For the others parts, eight office building types were examined with regard to their potential to be zero energy buildings. The buildings have different shapes and energy demands and were selected to define volumetric guidelines for zero energy buildings. A detailed energy balance analysis using energy demand and generation, as well, load matching and grid interaction indices for different time periods were used. In addition, alterations on the buildings' volumetries were made by changing the number of storeys to lead each volumetry's limits.

5.2.1 Developing optimal and zero energy models

Some steps were necessary to reach a zero energy building from the prototype (inefficient) office building case. Initially, the prototype building was transformed into an optimal building (energy-efficient or low energy building) in order to minimize its electricity demand. Then, PV panels were applied / integrated on the envelope to generate the necessary electricity to achieve an equalized energy balance. The process and results obtained are described in the following two subsections.

5.2.1.1 Optimal case

First, the surfaces and internal gains of the prototype case were evaluated by calculating detailed heat balances. With the heat balance the biggest energy consumption sources of the air-conditioning, which in Brazil is the biggest energy consumption, can be identified. Figure 5.12 shows the detailed heat balance with gains and losses for the prototype case for a period of one year. The analysis was performed for Florianopolis and Fortaleza separately for the occupation period (8 h-16 h), shown as gray bars and for a whole day (24 h), shown as black bars.



(a) (b)

Figure 5.12: Heat balance of the building for the prototype case in Florianopolis (a) and Fortaleza (b).

Artificial lighting, equipment, people and windows always cause a heat gain. The heat gains are mostly compensated by heat losses through the envelope, i.e. principally through the ground floor, by infiltration and by cooling. According to the Figure 5.12, the window is the surface causing highest heat gains in both cities. In Florianopolis much heat is lost through the surfaces (walls, ground floor and ceiling), cooling and air changes. In Fortaleza, cooling is the main source to remove heat from the environment. The annual energy consumption is presented in Figure 5.13. As expected in Fortaleza required the highest value energy demand for cooling, which is three times higher than in Florianopolis.

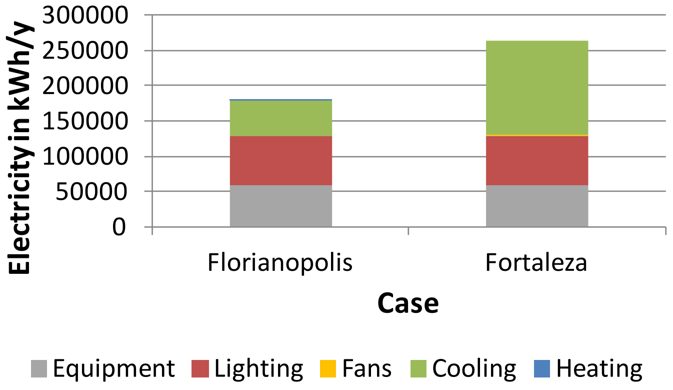


Figure 5.13: Annual energy consumption for prototype case in Florianopolis and Fortaleza.

The optimal case (energy-efficient building) was derived from the prototype case by modifying the office building to attain an energy efficiency of class 'A' for the envelope, lighting and cooling as specified by the Brazilian energy efficiency labeling system (RTQ-C)

[24]. Table 5.6 summarizes all requirements and actually achieved parameters. A detailed explanation is given below.

<table>
<tr><td colspan="5">**Requirements for non-residential buildings**</td></tr>
<tr><td colspan="5">**Envelope (30 %)**</td></tr>
<tr><td colspan="5">Prerequisites</td></tr>
<tr><td>Bioclimatic zone</td><td>Z3: Florianopolis</td><td>**Realized**</td><td>Z8: Fortaleza</td><td>**Realized**</td></tr>
<tr><td>U_{roof} in W/(m² K)</td><td>≤ 1.0</td><td>0.25</td><td>≤ 1.0</td><td>0.25</td></tr>
<tr><td rowspan="2">U_{wall} in W/(m² K)</td><td rowspan="2">≤ 3.7</td><td rowspan="2">3.1</td><td>≤ 2.5, for Cth < 80 kJ/(m² K)</td><td>0.39</td></tr>
<tr><td>≤ 3.7, for Cth > 80 kJ/(m² K)</td><td>Cth = 246</td></tr>
<tr><td>α_{roof}</td><td>≤ 0.50</td><td>0.25</td><td>≤ 0.50</td><td>0.25</td></tr>
<tr><td>α_{wall}</td><td>≤ 0.50</td><td>0.25</td><td>≤ 0.50</td><td>0.25</td></tr>
<tr><td colspan="5">Consumption indicator (Equation)</td></tr>
<tr><td colspan="5">Window area (WWR)</td></tr>
<tr><td colspan="5">Shading devices (AHS/AVS)</td></tr>
<tr><td colspan="5">Glass type (SHGC)</td></tr>
<tr><td colspan="5">Dimensions of the building (FA/FF)</td></tr>
<tr><td colspan="5">Brazilian bioclimatic zoning (Z1 to Z8)</td></tr>
<tr><td colspan="5">**Artificial Lighting (30 %)**</td></tr>
<tr><td colspan="4">For office buildings</td><td>**Realized**</td></tr>
<tr><td>Method 1</td><td>Building area (office)</td><td colspan="2">9.7 W/m²</td><td>9.69 W/m²</td></tr>
<tr><td>Method 2</td><td>Building activities (office)</td><td colspan="2">11.9 W/m²</td><td>9.69 W/m²</td></tr>
<tr><td colspan="5">**Cooling (40 %)**</td></tr>
<tr><td colspan="4" rowspan="2">Evaluated by PBE/INMETRO
(Level A > COP 3.20 W/W)</td><td>**Realized**</td></tr>
<tr><td>COP 4.31</td></tr>
</table>

Table 5.6: Summary of the parameters required by RTQ-C for a class 'A' energy efficient building.

a) Envelope

For the thermal transmittance of the external walls, 3.1 W/(m² K) was used in Florianopolis and 0.39 W/(m² K) was used in Fortaleza. For the roof a transmittance of 0.25 W/(m² K) was used for both cities, as well as an absorptance coefficient of 0.25 for the walls and the roof (Table 5.7). These values were defined based on the climatic characteristics of the cities located in different bioclimatic zones[10] in Brazil and based on values from a literature review [173]. The choice of these values could also be confirmed by the simulation results for the heat balance (see chapter 3 for more information about the studied climates).

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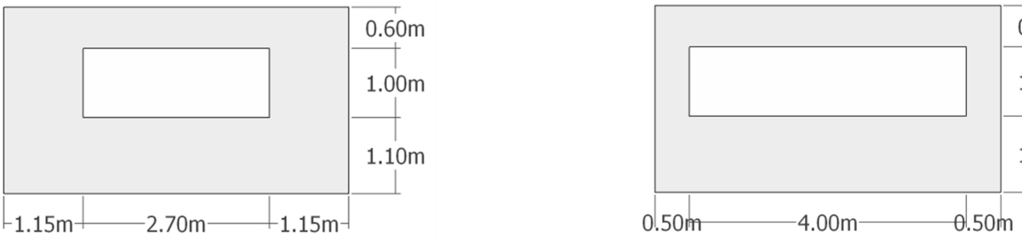
[10] The Brazilian territory was divided into eight climatic zones. The annex A of ABNT NBR 15220 presents the results of 330 cities whose climates were classified [5].

Material	**Thickness in m**	**λ in W/(m K)**	**ρ in Kg/m^3**	**cp in J/(kg K)**	**Cth in kJ/(m^2 K)**	**U in W/(m^2 K)**	**α**
Roof							
Concrete slab (CCA)	0.2	0.17	400	1000	102	0.25	0.25
Air space resistance		R = 0.18					
Isolation (polyurethane)	0.07	0.03	30	1670			
Plaster	0.03	0.35	750	840			
Exterior wall - Florianopolis							
Plaster	0.07	1.15	1300	1000	208	3.10	0.25
Brick	0.014	0.90	1000	920			
Brick	0.014	0.90	1000	920			
Plaster	0.07	1.15	1300	1000			
Exterior wall - Fortaleza							
Plaster	0.025	1.15	1300	1000	116	0.39	0.25
Isolation (polyurethane)	0.05	0.03	30	1670			
Concrete slab (CCA)	0.12	0.17	400	1000			
Plaster	0.025	1.15	1300	1000			

Table 5.7: Physical material properties [4], [121].

The office window size was change from a WWR of 20 % to 30 %, to increase the available daylight (Figure 5.14). To further increase the available daylight in the office, especially in parts distant from the main window, an interior upper single clear glass window was added into the hallway wall for each room. The single clear glass of the windows in the exterior walls was replaced by a double low-E glazing.

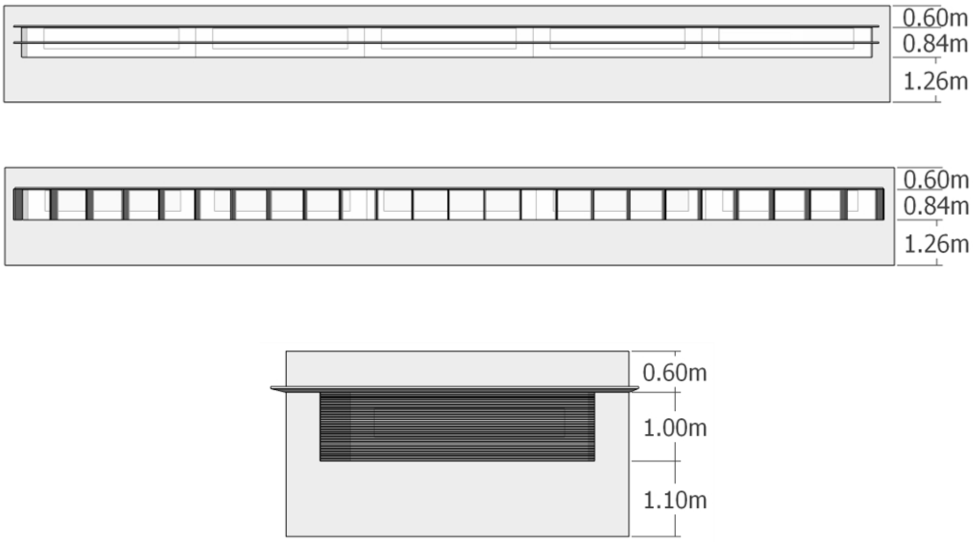


(a)

(b)

Figure 5.14: Window to wall ratio (WWR) for windows' office of the prototype case of 20 % (a) and for the optimal case of 30 % (b).

Shading devices were added to protect the windows against direct solar radiation and heat gains according to their orientation and climatic demands. In Florianopolis only overhangs (0.50 m x 24 m) were used to protect the hallway window, whilst in Fortaleza overhangs (1 m x 24 m) and fins (1 m x 0.84 m) were added. For the South side office windows, fixed overhangs (1 m x 4 m) and mobile venetian blinds were applied in Fortaleza (Figure 5.15). To choose the best protection option for the office windows in Fortaleza, a parametric study with different combinations of shading devices was made. The chosen combination achieved a reduction of 2 % of the annual energy consumption, results are presented in Appendix A.4.



(a)

(b)

(c)

Figure 5.15: Shading devices for North hallway windows in Florianopolis (a) and Fortaleza (b) and for South office windows in Fortaleza (c).

b) Lighting

The installed lighting power was reduced from 12 W/m² to 9.69 W/m², which is the maximum permitted value according to RTQ-C for a Level 'A' office building. In addition, an automatic dimming system controlling artificial lighting was used in order to ensure that artificial lighting was turned off when the available daylight reached 500 lux in the office room and 100 lux in the hallway [6].

c) Cooling

An air conditioning system with a COP of 4.31 was chosen based on the PBE/INMETRO[11] list to replace the air conditioning used in the prototype case with a COP of 2.8.

d) Equipment

The internal gains for equipment remained 9.7 W/m². However, the elevators used in the prototype case were replaced by 33 % more efficient ones.

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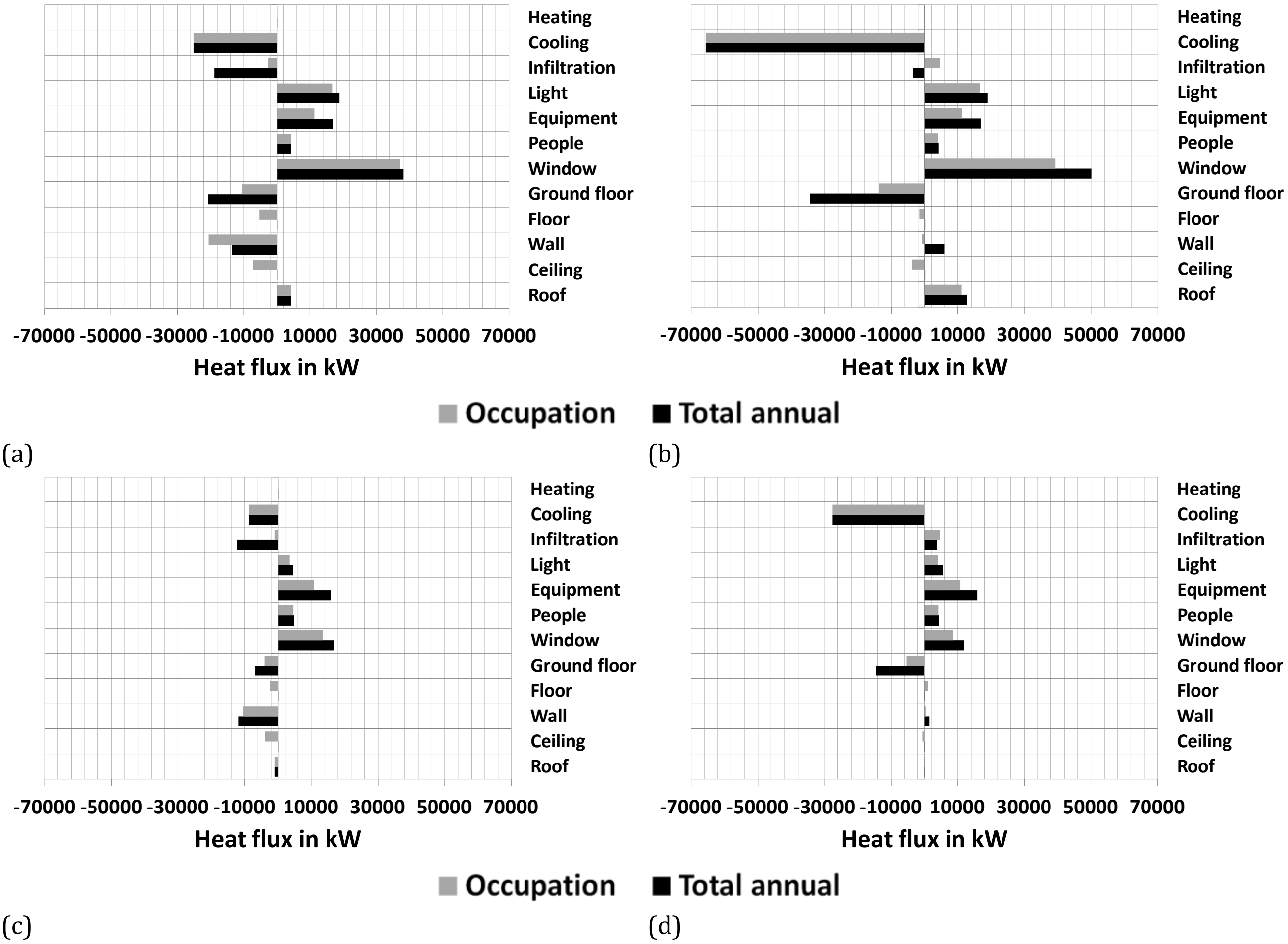
[11] The Brazilian labeling program (*Programa Brasileiro de Etiquetagem* - PBE), coordinated by INMETRO, provides information on the performance of products, considering attributes such as energy efficiency that can influence consumers' choice [129].

Except this, the infiltration rate was reduced from 1 ACH to 0.7 ACH for office rooms in Fortaleza and to 3 ACH for the corridor in both cities. The minimum air renovation of 27 m^3/hour/person as recommended by NBR 16401-1 [7] for air-conditioned environments was considered.

Figure 5.16 presents the heat balance obtained with the transformation of the prototype case into optimal case. The heat gains from the roof in the prototype case could be eliminated by exchanging building materials. Regarding the development of the building along the different cases the reduction for lighting and cooling were biggest. The reduction of the cooling was mainly possible due to less heat entering through the windows.



(a) (b) (c) (d)

Figure 5.16: Heat balances of the building for the prototype case in Florianopolis (a) and Fortaleza (b) and optimal cases in Florianopolis (c) and Fortaleza (d).

In Figure 5.17 the energy balance for the prototype and optimal case are presented. For both cities approximately a bisection of the annual energy consumption, from the prototype case to the optimal case, was achieved. Effectively, the reduction is 50 % in Florianopolis and 53 % in Fortaleza.

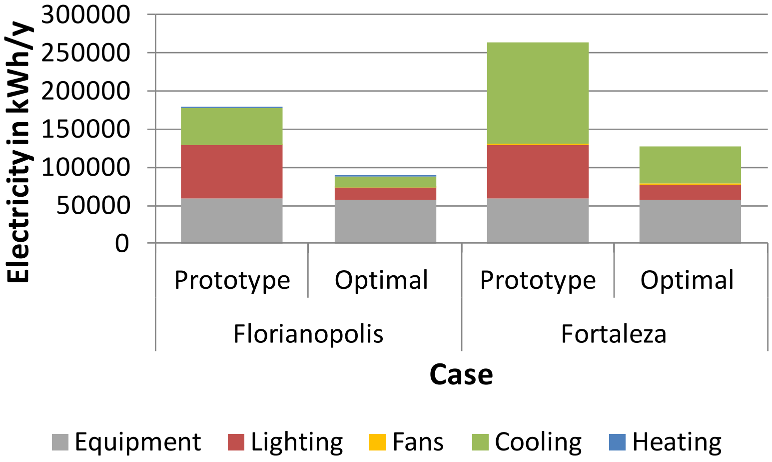


Figure 5.17: Annual energy consumption for prototype and optimal cases in Florianopolis and Fortaleza.

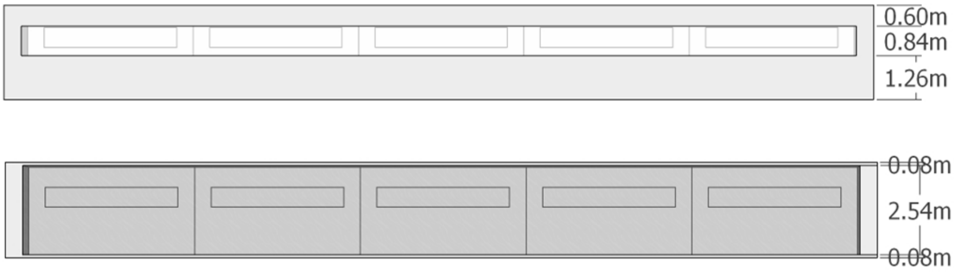
5.2.1.2 Zero energy case

The zero energy case was derived from the optimal case by the application of solar energy technologies to the building's envelope. Photovoltaic modules were applied, as BAPV on the roof and BIPV in East and West facades; semi-transparent PV windows were used in the North facade for the hallway windows; and in Fortaleza PV modules were also used on the overhangs on the South facade.

In addition, the WWR of the hallway windows was increased from 20 % to 90 % (Figure 5.18), where semi-transparent PV windows were used. The single clear glass of the internal windows was replaced by single low-E glass and insulation was added to the internal wall between the hallway and the offices (Table 5.8). These modifications were necessry due to the heat generated by the PV windows.

Material	Thickness in m	λ in W/(m K)	ρ in Kg/m³	cp in J/(kg K)	Cth in kJ/(m² K)	U in W/(m² K)	α
Interior wall - hallway							
Plaster	0.07	1.15	1300	1000	245	0.35	0.50
Isolation (polyurethane)	0.05	0.03	30	1670			
Concrete slab (CCA)	0.15	0.17	400	1000			
Plaster	0.07	1.15	1300	1000			
Interior window - hallway							
Low-E 3#	0.003					5.77	

Table 5.8: Physical material properties [4], [121].



(a)

(b)

Figure 5.18: Window to wall ratio (WWR) for hallway windows of the prototype case of 20 % (a) and for the optimal case of 90 % (b).

The detailed characteristics of the building models that were modified from the optimal to the zero energy case are presented in Table 5.9. The other parameters remained constant.

Parameters	**Cases**					
	Prototype case		**Optimal case**		**Zero energy case**	
City	Florianopolis	Fortaleza	Florianopolis	Fortaleza	Florianopolis	Fortaleza
$WWR_{Hallway}$ in %	20	20	20	20	90	90
WWR_{Office} in %	20	20	30	30	30	30
$U_{Window-outside}$ in W/m^2 K	5.82	5.82	1.68	1.68	1.68/1.67	1.68/1.67
$VT_{Window-outside}$	0.88	0.88	0.70	0.70	0.70/0.23	0.70/0.23
$SHGC_{Window-outside}$	0.82	0.82	0.40	0.40	0.40/0.22	0.40/0.22
$U_{Window-inside}$ in W/(m^2 K)	-	-	5.82	5.82	5.77	5.77
$VT_{Window-inside}$	-	-	0.88	0.88	0.79	0.79
$SHGC_{Window-inside}$	-	-	0.82	0.82	0.47	0.47
Shading device	no	no	yes	yes	no	yes
Venetians	no	no	no	yes	no	yes
U_{wall} in W/(m^2 K)	2.47	2.47	3.1	0.39	3.1	0.39
U_{roof} in W/(m^2 K)	2.42	2.42	0.25	0.25	0.25	0.25
Wall: Thermal capacity in kJ/(m^2 K)	200	200	208	116	208	116
Roof: Thermal capacity in kJ/(m^2 K)	187	187	102	102	102	102
α_{wall}	0.65	0.65	0.25	0.25	0.25	0.25
α_{roof}	0.70	0.70	0.25	0.25	0.25	0.25
Office light in W/m^2	12	12	9.69	9.69	9.69	9.69
Corridor light in W/m^2	5	5	5	5	5	5
Lighting control office	-	-	dimmer	dimmer	dimmer	dimmer
Illuminance office in lux	-	-	500	500	500	500
Illuminance corridor in lux	-	-	100	100	100	100
Elevator in W/m^2	367.5	367.5	209.1	209.1	209.1	209.1
Infiltration office	1 ACH	1 ACH	1 ACH	0.7 ACH	1 ACH	0.7 ACH
Infiltration corridor	1 ACH	1 ACH	3 ACH	3 ACH	3 ACH	3 ACH
Efficiency in COP in W/W	2.8	2.8	4.31	4.31	4.31	4.31

Table 5.9: Modified parameters to reach the zero energy case.

Table 5.10 presents the installed PV area and its installed nominal power[12] (INP) for the zero energy case in Florianopolis and Fortaleza. For this analysis, no surrounding or obstructions were considered.

Surface	**Roof**		**East facade**		**West facade**		**Window**		**Overhangs**	
City	Area in m²	INP in kWp	Area in m²	INP in kWp	Area in m²	INP in kWp	Area in m²	INP in kWp	Area in m²	INP in kWp
Florianopolis	138.6	27.9	214	27.8	214	27.8	670	20.1	-	-
Fortaleza	161.7	32.5	214	27.8	214	27.8	670	20.1	275	35.7

Table 5.10: Installed PV power per surface.

The heat balance comparing the three cases (prototype, optimal and zero energy) is shown in Figure 5.19. For the zero energy case, the windows caused the largest heat gain, as it was in the prototype case. This happens due to the bigger windows in the corridor and the additional heat generated by PV windows and it must be seen in context with the reduced lighting energy and the generated electricity which overcompensate the additional heat gain. Anyway a further reduction of the heat gain by the PV windows would be desirable.

The office building's annual energy consumption for the three cases (prototype case, optimal case, and zero energy case) and for the zero energy case the generated electric energy, for Florianopolis and Fortaleza are presented in Figure 5.20. As presented before, the reduction from prototype to optimal building was almost 50 %. For the zero energy case 1 % more energy was generated than consumed in Florianopolis and 13 % in Fortaleza which can be fed into the electric grid. In general, in Fortaleza the energy consumption is higher than in Florianopolis, but also more energy is generated by the PV modules.

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[12] The installed nominal power was calculated by the efficiency of the module (efficiency * solar radiation / area * area (STC)), provided by the manufacturer, multiplied by the installed PV area [51].

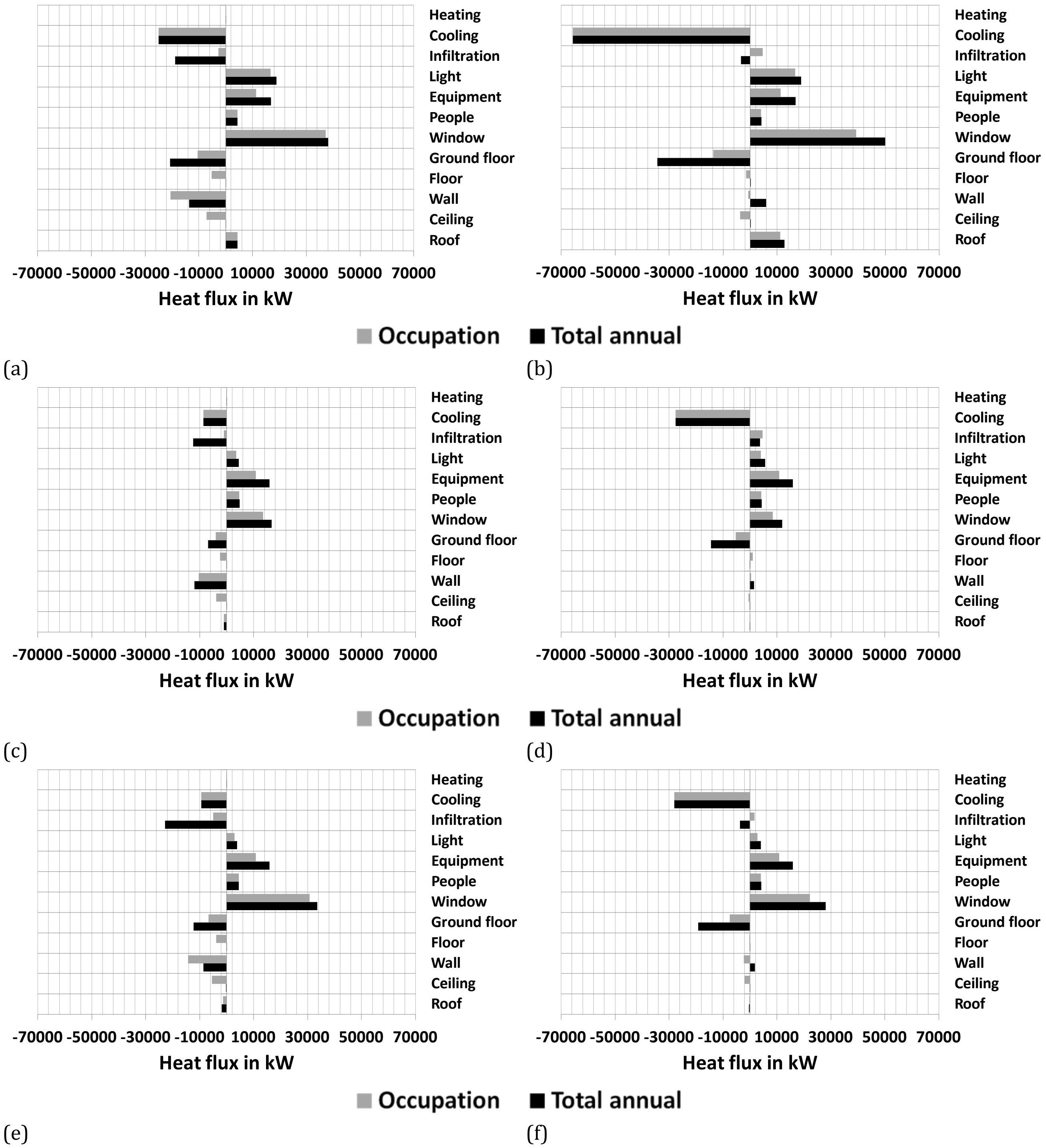


Figure 5.19: Heat balance of the building for the prototype case in Florianopolis (a) and Fortaleza (b), optimal case in Florianopolis (c) and Fortaleza (d) and zero energy case in Florianopolis (e) and Fortaleza (f).

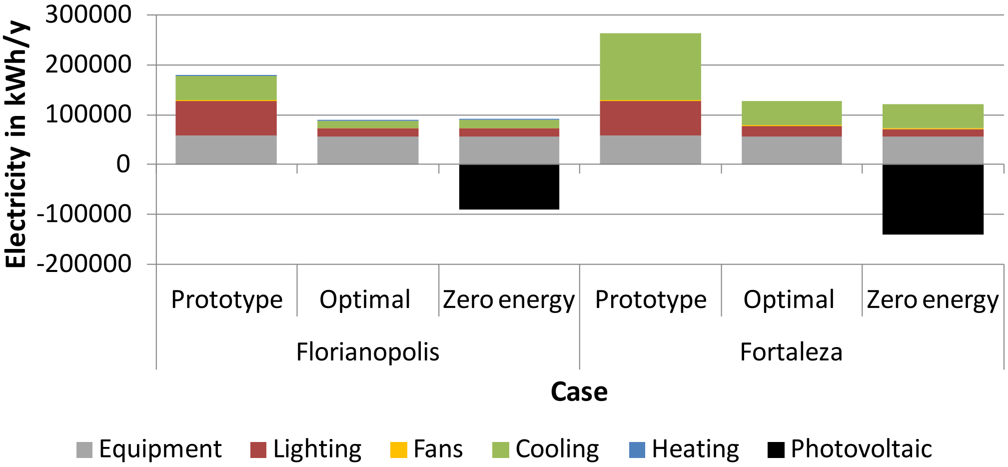
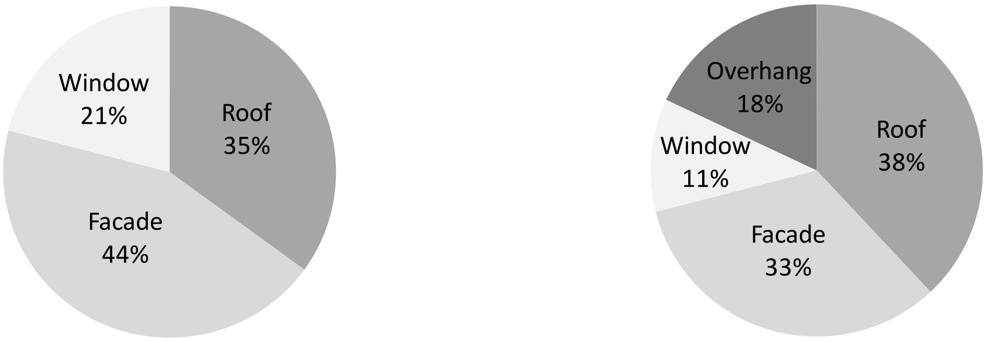


Figure 5.20: Annual energy consumption and generation for prototype, optimal and zero energy case in Florianopolis and Fortaleza.

Generated energy

The distribution of the generated energy according to the different PV installation surfaces can be seen in Figure 5.21. The photovoltaic modules on the roof produced 35 % and 38 % of the energy in Florianopolis and Fortaleza, respectively. Despite having less installed PV area than the other surfaces, this is expected as the modules have the best orientation relative to the sun and they have the highest efficiency.

The sum of the energy generated by the facade modules (East and West) is 44 % and 33 % of the totally produced energy. In Fortaleza the modules on the overhangs of the South facade generated 18 %. Finally, the semi-transparent PV windows in the North facade generated 21 % in Florianopolis and 11 % in Fortaleza.



(a) (b)

Figure 5.21: Generated energy from the different surfaces for Florianopolis (a) and Fortaleza (b).

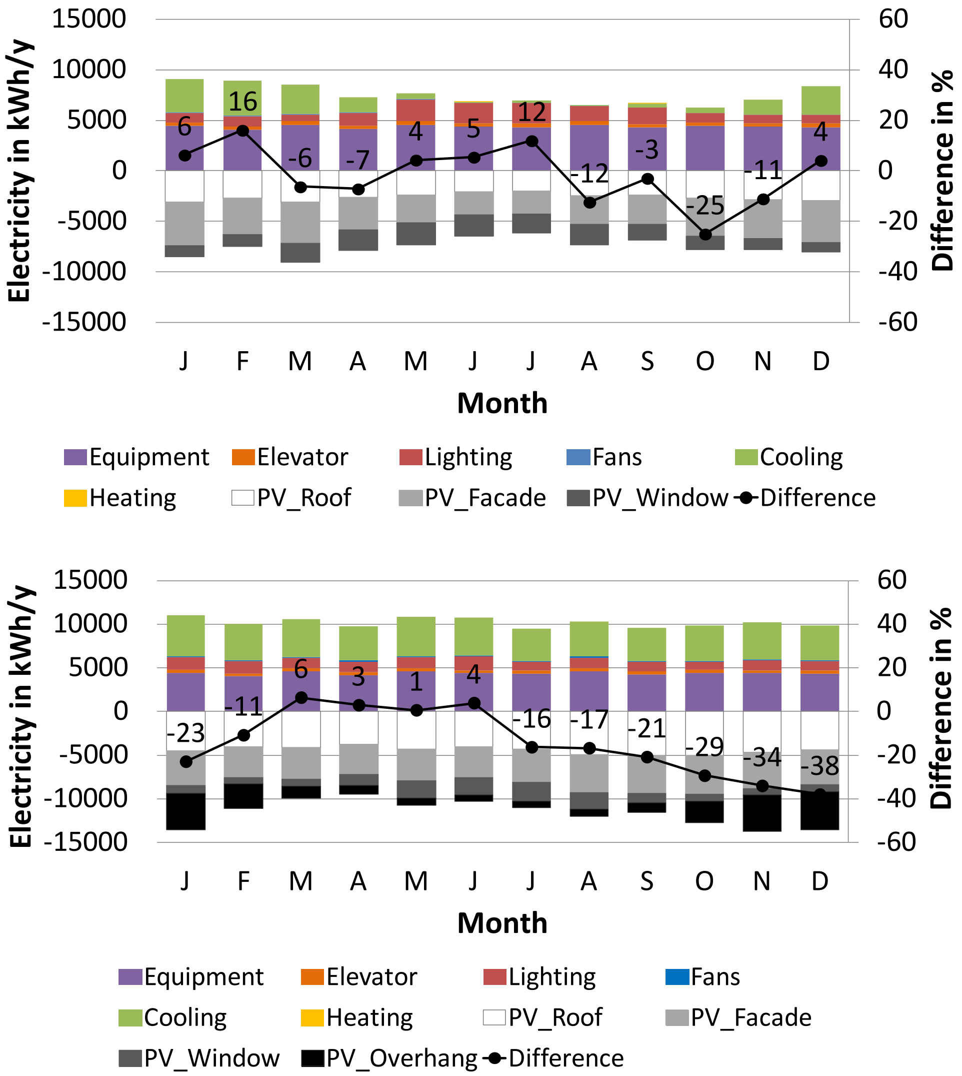
It must be noted that for this analysis a large portion of the building envelope was covered by PV modules. Depending on the orientation the efficiency and the installation costs a payback analysis should be realized to determine the benefit of their application. However, as it is known, the price of PV modules is decreasing significantly which makes their application possible for aesthetic reasons where energy generation is just a benefit.

Another important parameter for a PV application is the surrounding and its influence on the solar irradiation, e.g. by shading the modules. A detailed investigation of the shading influence is given in section 5.3.

Energy balance

The monthly energy balance for the zero energy case in Florianopolis and Fortaleza is shown in Figure 5.22. The positive columns represent the energy consumption by the building, and the negative columns represent the generated energy. The final balance between the consumed and generated energy for each month is plotted with black dots; negative values mean that energy can be fed into electricity grid, positive values mean a resulting energy consumption.

According to the graphics, Florianopolis has less energy consumption and generation in winter months (Jun-Aug). For these months cooling is rarely used and heating was not necessary. Although it should not be considered as a heating strategy, the internal gains were sufficient to heat the building when necessary. Analyzing the final energy balance, only in July the energy consumption was higher than the generated energy. In Fortaleza, cooling is necessary during the whole year. The energy demand is higher in Fortaleza than in Florianopolis and the differences between summer and winter months are smaller. More energy was produced in Fortaleza, and more photovoltaic modules were necessary to satisfy the energy demand.



a)

(b)

Figure 5.22: Monthly energy balance for the zero energy case in Florianopolis (a) and Fortaleza (b).

Regarding the results it is remarkable that for both cities the generated electricity from the different PV surfaces have different behaviors through the course of one year, or more precisely for summer and winter months. While the PV on the roof, facade and overhangs generate more energy in summer months, the PV window generates more in winter months. For the overhangs in Fortaleza the energy generation decrease significantly for the winter months; on the roof it remains almost constant. It is clear that different PV technologies and applications can complement each other to achieve a zero energy balance.

5.2.2 Determining ZEB standard types

For this analysis eight office building types with different dimensions were used. After transforming them into optimal buildings (section 5.2.1), PV modules were applied / integrated to the envelope to achieve an equalized energy balance. The installed PV area and nominal power (INP) for each surface, as well as, the total PV area and total installed nominal power for each building type are shown in Tables 5.11 and 5.12 for both cities. The PV models were applied according to the buinding energy demand, anyway for some building types the surface area was not sufficient to generate the required energy.

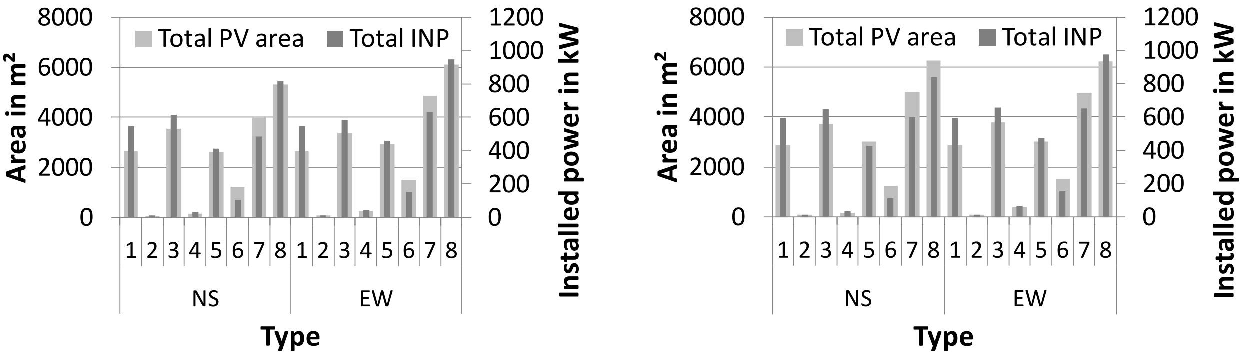
Type		**Roof**		**Facade**		**Solar protection**		**Window**		**Total PV Area in m^2**	**Total INP in kWp**
		Area in m^2	**INP in kWp**	**Area in m^2**	**INP in kWp**	**Area in m^2**	**INP in kWp**	**Area in m^2**	**INP in kWp**		
North-South	T1	2633	529							2633	529
	T2	65	13							65	13
	T3	1787	359	1270	165	450	59	41	1	3548	584
	T4	164	33							164	33
	T5	706	142	1620	211	300	39			2626	391
	T6	139	28	428	56			670	20	1237	104
	T7	1075	216	1264	164	354	46	1291	39	3984	465
	T8	1235	248	3214	418	850	111			5299	777
East-West	T1	2633	529							2633	529
	T2	67	14							67	14
	T3	1808	363	1270	165	225	29	81	2	3384	560
	T4	147	30	110	14					257	44
	T5	706	142	1620	211	600	78			2926	430
	T6	147	30	428	56	275	36	670	20	1520	141
	T7	1077	217	1264	164	1238	161	1291	39	4870	580
	T8	1205	242	3214	418	1700	221			6119	881

Table 5.11: Installed PV area and PV power for each surface in Florianopolis.

Type		**Roof**		**Facade**		**Solar protection**		**Window**		**Total PV Area in m^2**	**Total INP in kWp**
		Area in m^2	**INP in kWp**	**Area in m^2**	**INP in kWp**	**Area in m^2**	**INP in kWp**	**Area in m^2**	**INP in kWp**		
North-South	T1	2873	577							2873	577
	T2	76	15							76	15
	T3	1932	388	1270	165	450	59	81	2	3733	614
	T4	164	33							164	33
	T5	794	160	1620	211	600	39			3014	409
	T6	162	33	428	56			670	20	1260	108
	T7	1210	243	1264	164	1238	115	1291	39	5002	561
	T8	1338	269	3214	418	1700	111			6252	797
East-West	T1	2873	577							2873	577
	T2	76	15							76	15
	T3	1985	399	1270	165	450	59	81	2	3786	625
	T4	176	35	220	29					396	64
	T5	794	160	1620	211	600	78			3014	448
	T6	162	33	428	56	275	36	670	20	1535	144
	T7	1197	241	1264	164	1238	161	1291	39	4990	604
	T8	1323	266	3214	418	1700	221			6237	905

Table 5.12: Installed PV area and PV power for each surface in Fortaleza.

Figure 5.23 shows the relation between the total installed PV area and total installed PV power for each building type, orientation and city. Depending on the efficieny of the PV panels used, some buildings have more installed PV area and less installed power (e.g. T7) than others (e.g. T1).



(a) (b)

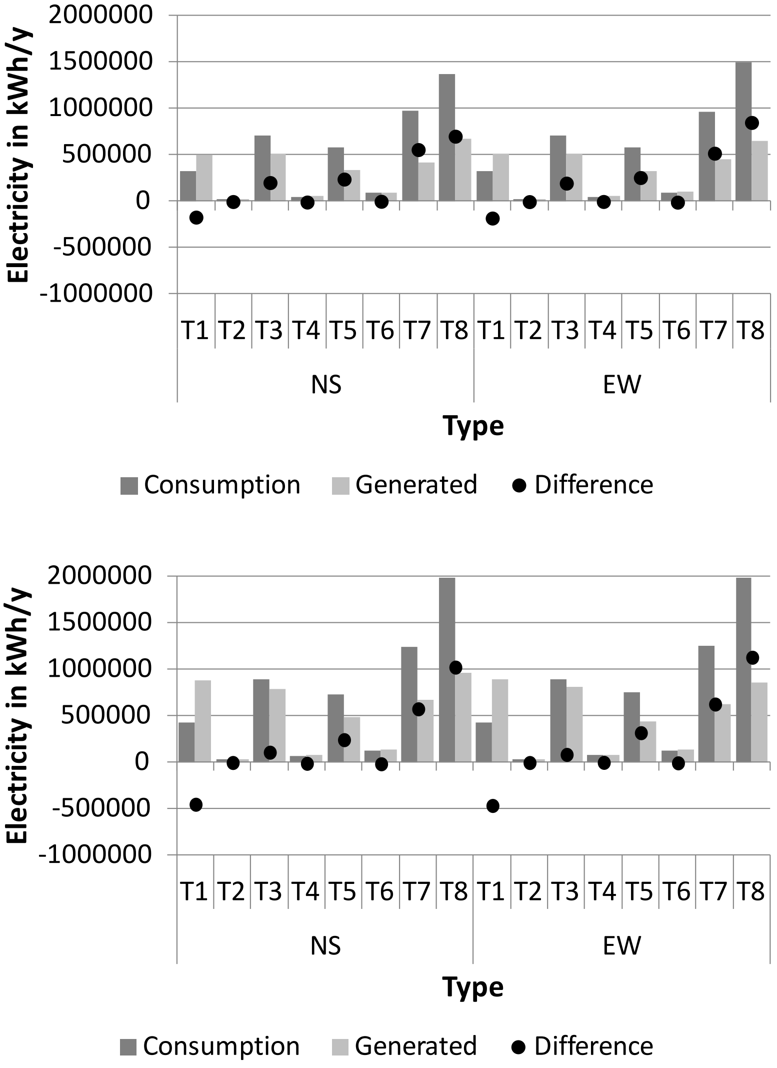
Figure 5.23: Relationship between total installed PV area and total installed PV power for North-South (NS) and East-West (EW) orientations in Florianopolis (a) and Fortaleza (b).

5.2.3 Classifying the building types: ZEB or nearly ZEB

The electricity demand and generation for the eight office building types, for the two orientations North-South and East-West for Florianopolis and Fortaleza is presented in Figure 5.24. The columns are the electricity demand and the generated energy. The dots are the differences between the both, which means the resulting energy consumption or generation. Models marked with a light green bar reached a zero energy balance with the actual PV application.

Acoording to the Figure, the types T1, T2, T4 and T6 reached a zero energy balance for different orientations and climatic conditions. The orientation showed few alterations on energy consumption and generation; whilst the climatic conditions given by the city made a big difference. As expected, Fortaleza has a higher energy demand than Florianopolis, however more energy is produced there as well. The other types, T3, T5, T7 and T8 can be classificated as nearly zero energy buildings, since they produce almost 50 % of the energy they need.

T1 generates much more electricity than it uses. This happens due to the amount of PV modules applied on the avaiable roof surface. This surplus of energy can be delivered to the electric network or be distributed among neighboring buildings. However, it is noteworthly that no obstructions were considered for this analysis, which could reduce the genareted energy. In contrast, the T7 and T8 have much more installed PV area on the envelope than T1. However due to their volumetry and their relation between floor and net area, the installed PV power was not sufficient to satisfy the annual energy demand. For these buildings more efficient PV modules could be applied and / or other types of renawable energy must be used to complement the demand.



(a)

(b)

Figure 5.24: Electricity demand and generation for the eight types (T1 to T8) with North-South (NS) and East-West (EW) orientation in Florianopolis (a) and Fortaleza (b). The difference is the subtraction between energy consumption and generated energy.

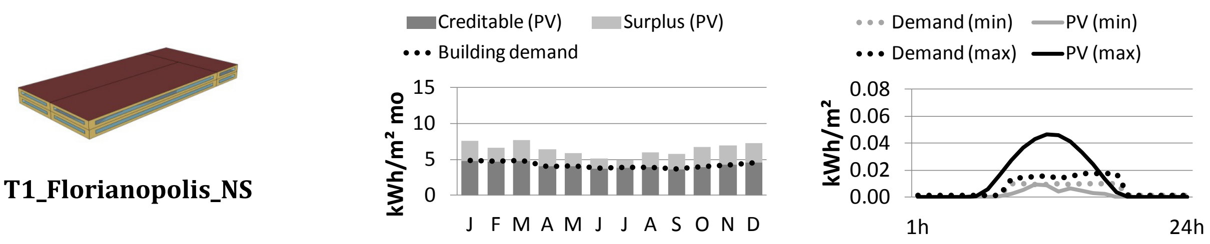
5.2.4 Load matching and grid interaction analysis

This section presents the energy balance analysis for the eight types (T1-T8) in Florianopolis and Fortaleza. The models were analyzed using the import / export method, which considers the relationship (exchanges) between the building and the electric grid. Besides, the demand / generation method is also presented for a better insight on the remaining shortfall of on-site supply.

For a detailed import / export energy balance evaluation, hourly, daily and monthly analyses for load matching and grid interaction were calculated. With the help of these methods, it is possible to know in detail when power is feed in or received from the electric grid and in which hours the building peak demand is. It is a way to analyze more precisely when the energy grid or an energy storage system, e.g. batteries have to be used or other types of renewable energy could complement to reach a zero balance.

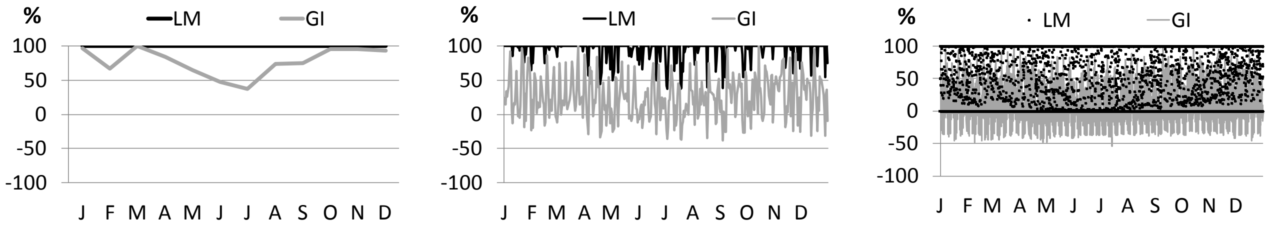
The results presented below are for North-South orientation, the ones for East-West orientation can be found in appendix A.5. Subfigures (b) and (c) show the building demand and generated energy analysis for each model, where the monthly analysis is presented in (b) and the daily analysis in (c). For the daily analysis the weekday with highest and lowest energy generation were chosen for the Figures. The layout of the Figures is based on [178].

Load matching and grid interaction analysis are presented in subfigures (d), (e) and (f), which are monthly, daily and hourly values, respectively. The annual results are presented at the end to summarize the analysis. The load matching index gives the percentage of the currently used energy that can be statisfied by the actual on-site generation. The grid interaction index represents the energy actually supplied by the grid, when the index is negative, or the energy fed into the grid, when the index is positive, in relation to the maximum magnitude of energy taken from the grid or fed into the grid within the regarded period. The annual grid index represents the standard deviation of the grid interaction, in other words, the fluctuation of the energy exchange of the building with the grid, higher values mean higher variation.



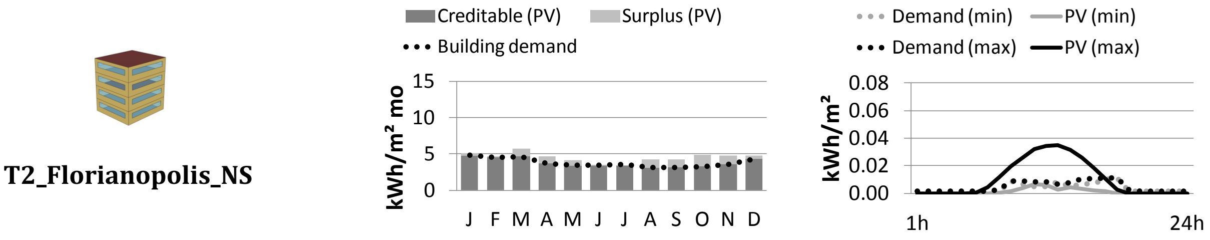
(a) (b) (c)

Figure 5.25: Building demand and generated energy for T1 (a) in monthly (b) and daily (c) profiles for North-South facade in Florianopolis.



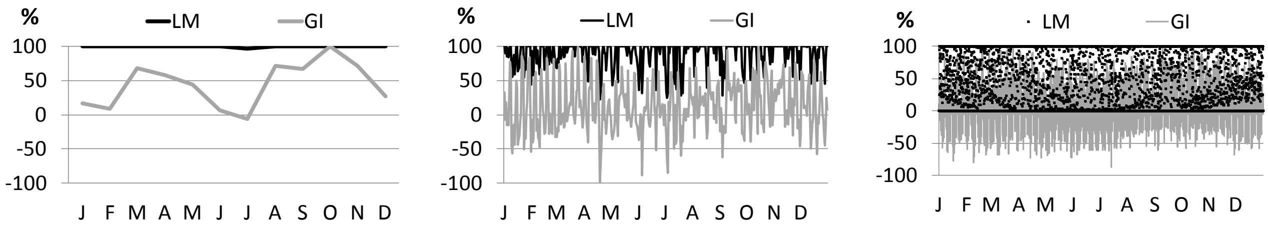
(d) (e) (f)

Figure 5.26: Load match (LM) and grid interaction (GI) for T1 in monthly (d), daily (e) and hourly (f) profiles for North-South facade in Florianopolis.



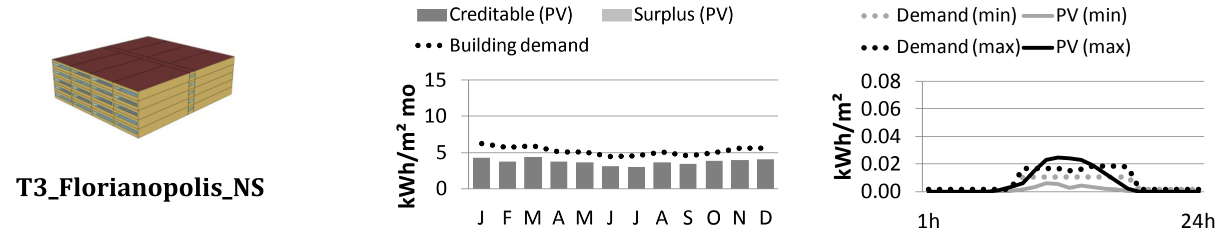
(a) (b) (c)

Figure 5.27: Building demand and generated energy for T2 (a) in monthly (b) and daily (c) profiles for North-South facade in Florianopolis.



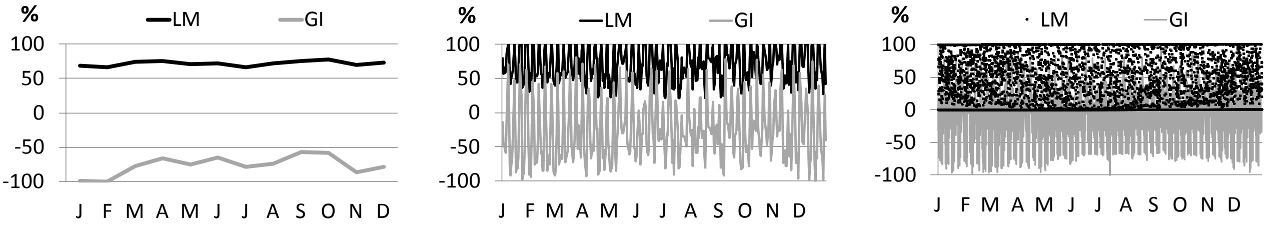
(d) (e) (f)

Figure 5.28: Load match (LM) and grid interaction (GI) for T2 in monthly (d), daily (e) and hourly (f) profiles for North-South facade in Florianopolis.



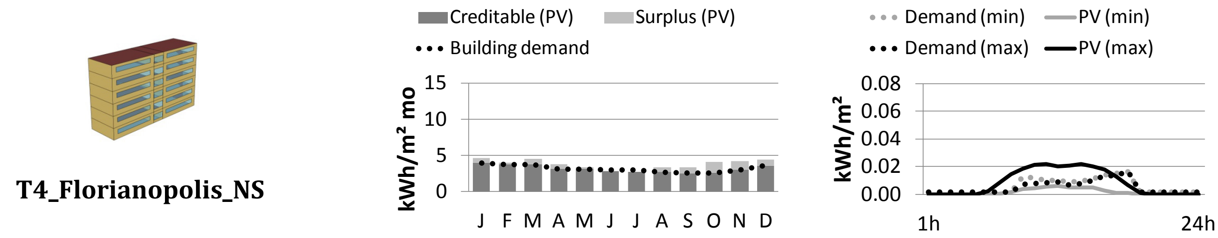
(a) (b) (c)

Figure 5.29: Building demand and generated energy for T3 (a) in monthly (b) and daily (c) profiles for North-South facade in Florianopolis.



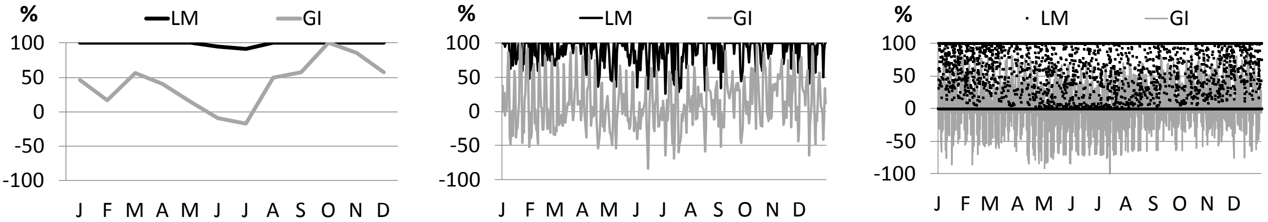
(d) (e) (f)

Figure 5.30: Load match (LM) and grid interaction (GI) for T3 in monthly (d), daily (e) and hourly (f) profiles for North-South facade in Florianopolis.



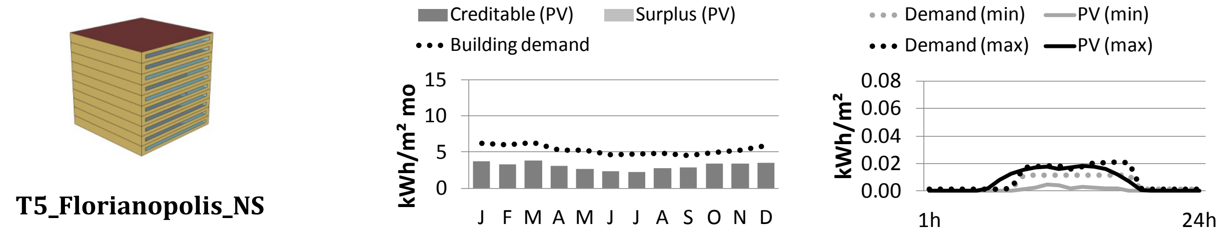
(a) (b) (c)

Figure 5.31: Building demand and generated energy for T4 (a) in monthly (b) and daily (c) profiles for North-South facade in Florianopolis.



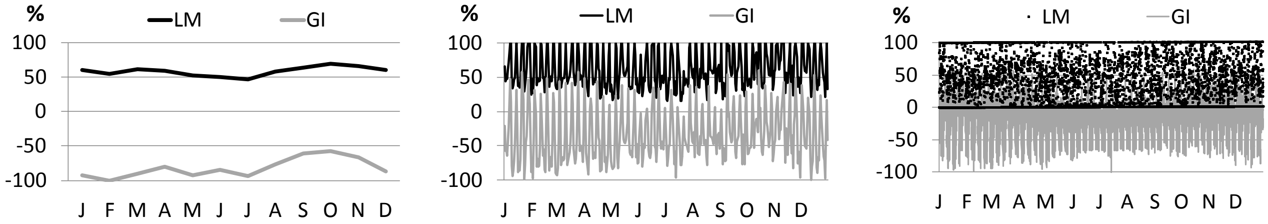
(d) (e) (f)

Figure 5.32: Load match (LM) and grid interaction (GI) for T4 in monthly (d), daily (e) and hourly (f) profiles for North-South facade in Florianopolis.



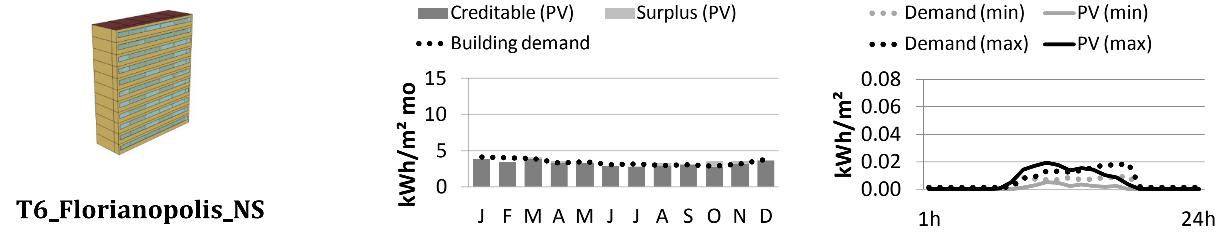
(a) (b) (c)

Figure 5.33: Building demand and generated energy for T5 (a) in monthly (b) and daily (c) profiles for North-South facade in Florianopolis.



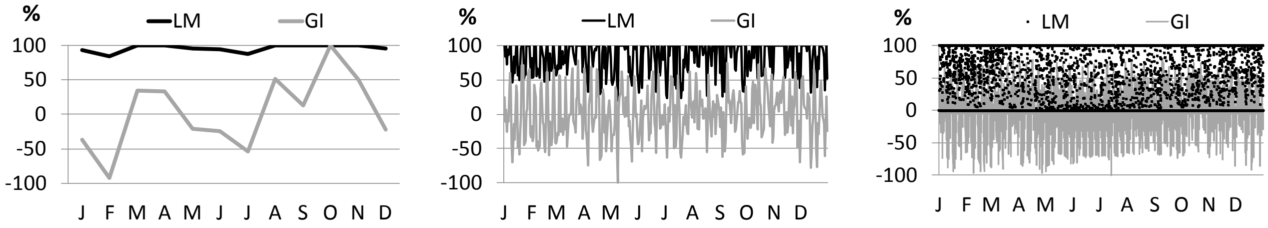
(d) (e) (f)

Figure 5.34: Load match (LM) and grid interaction (GI) for T5 in monthly (d), daily (e) and hourly (f) profiles for North-South facade in Florianopolis.



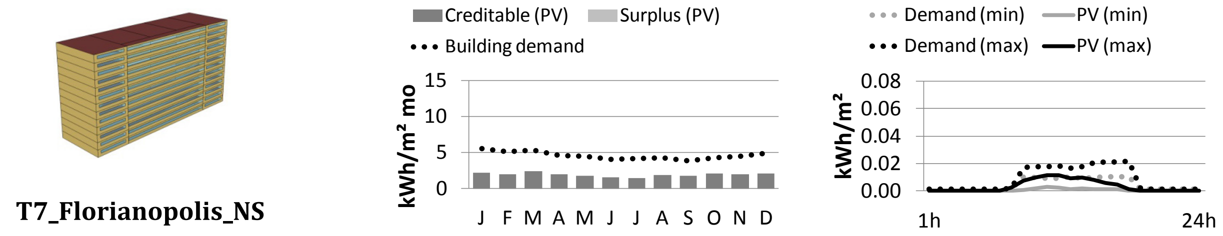
(a) (b) (c)

Figure 5.35: Building demand and generated energy for T6 (a) in monthly (b) and daily (c) profiles for North-South facade in Florianopolis.



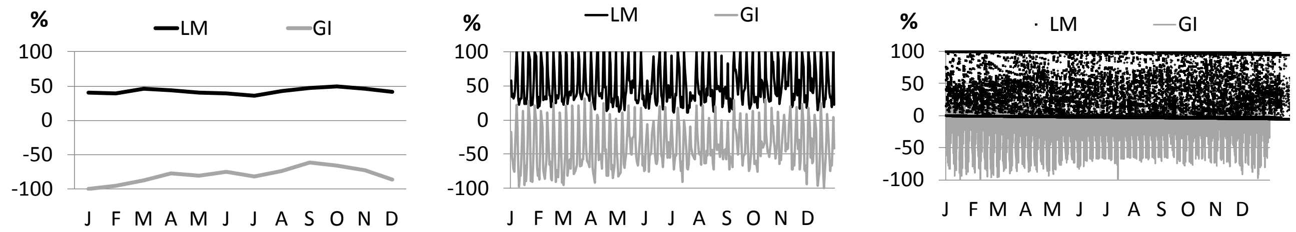
(d) (e) (f)

Figure 5.36: Load match (LM) and grid interaction (GI) for T6 in monthly (d), daily (e) and hourly (f) profiles for North-South facade in Florianopolis.



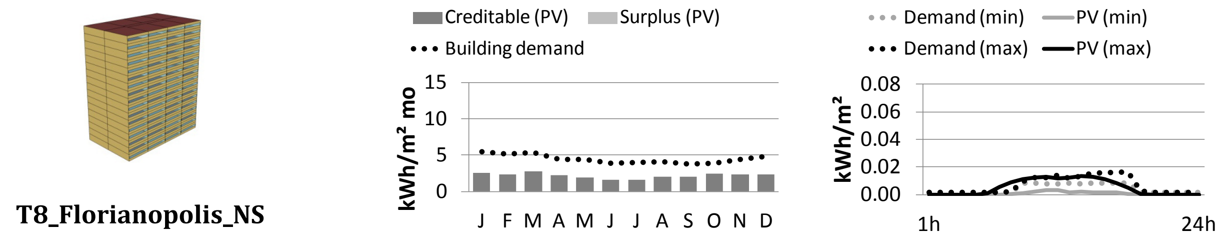
(a) (b) (c)

Figure 5.37: Building demand and generated energy for T7 (a) in monthly (b) and daily (c) profiles for North-South facade in Florianopolis.



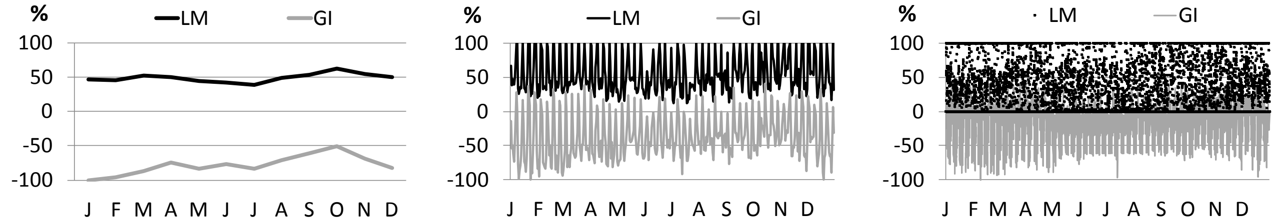
(d) (e) (f)

Figure 5.38: Load match (LM) and grid interaction (GI) for T7 in monthly (d), daily (e) and hourly (f) profiles for North-South facade in Florianopolis.



(a) (b) (c)

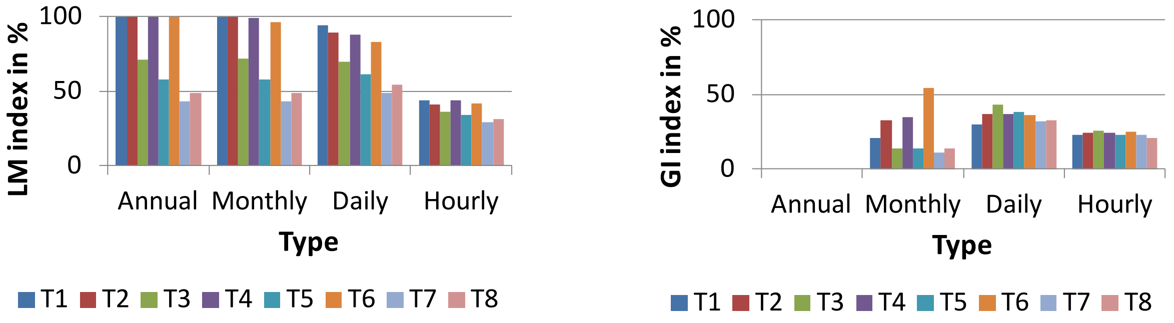
Figure 5.39: Building demand and generated energy for T8 (a) in monthly (b) and daily (c) profiles for North-South facade in Florianopolis.



(d) (e) (f)

Figure 5.40: Load match (LM) and grid interaction (GI) for T8 in monthly (d), daily (e) and hourly (f) profiles for North-South facade in Florianopolis.

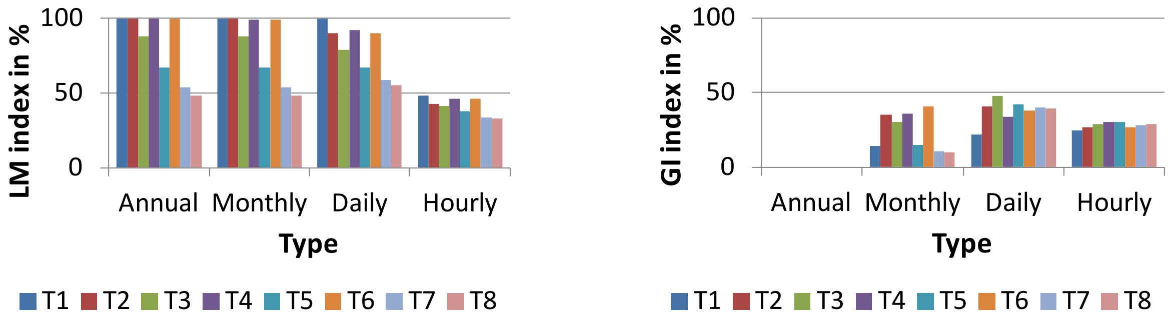
The figures above show that different analysis periods result in different match indices. The hourly analysis shows much lower values than monthly and daily analysis for the load matching index. This happens as during the night no energy is produced but still some energy is needed, e.g. for equipment. The grid interaction analysis has low and medium fluctuations for all models, with the highest value of 54 % for T6 in the monthly analysis. A summary for all eight types in Florianopolis oriented North-South is presented in Figure 5.41.



(a) (b)

Figure 5.41: Comparison of the load match (a) and grid interaction (b) indices with different time resolutions for the eight types in Florianopolis, with North-South orientation.

The load match / grid interaction analysis for North-South orientation in Fortaleza show similar values to the one of Florianopolis. The hourly analysis presented lower values than the monthly and daily analysis for the load matching index. The fluctuations in the grid interaction analysis were lower than in Florianopolis for some building types, with a peak value of 48 % for T3 in the daily analysis. A summary for the eight types in Florianopolis oriented North-South is presented in Figure 5.42, the detailed results can be seen in Appendix A.5.



(a) (b)

Figure 5.42: Comparison of the load match (a) and grid interaction (b) indices based on different time resolutions for the eight types in Fortaleza, with North-South orientation.

5.2.5 Preferable ZEB volumetries

This topic evaluates which of the presented volumetries are most suitable for ZEBs. For this analysis the volumetries of the eight used types were changed by adding or removing storeys, Tables 5.13 and 5.14 present the installed PV area and PV power for each new configuration in Florianopolis and Fortaleza. For this analysis PV modules were applied on all usable surfaces. In the table all evaluated configurations with different numbers of floors are presented. In general two altered configurations were required for each 'base' building type to find the limit for a ZEB configuration. Exceptions are T6_NS in Florianopolis and in Fortaleza T3_NS and T3_EW, where only two configurations were necessary to determine the limits.

Type		Floor	Roof		Facade		Solar protection		Window		Total PV Area in m^2	Total INP in kWp
			Area in m^2	INP in kWp	Area in m^2	INP in kWp	Area in m^2	INP in kWp	Area in m^2	INP in kWp		
North-South	T1	4	2633	529			640	83			3273	612
		3	2633	529			480	62			3113	592
		2	2633	529			320	42			2953	571
	T2	7	65	13			196	25			261	39
		6	65	13			168	22			233	35
		4	65	13			112	15			177	28
	T3	5	1787	359	1269	165	450	59	41	1	3547	584
		4	1787	359	1015	132	360	47	33	1	3195	539
		3	1787	359	761	99	270	35	25	1	2843	494
	T4	29	164	33	1057	137	687	89	212	6	2120	266
		28	164	33	1021	133	664	86	205	6	2053	258
		6	164	33	219	28	142	18	44	1	569	81
	T5	10	706	142	1620	211	300	39			2626	391
		4	706	142	648	84	120	16			1474	242
		3	706	142	486	63	90	12			1282	217
	T6	12	139	28	467	61			731	22	1336	110
		11	139	28	428	56			670	20	1236	104
	T7	13	1075	216	1264	164	354	46	1291	39	3983	465
		4	1075	216	389	51	109	14	397	12	1970	293
		3	1075	216	292	38	82	11	298	9	1746	274
	T8	17	1235	248	3213	418	850	111			5298	776
		5	1235	248	945	123	250	33			2430	404
		4	1235	248	756	98	200	26			2191	372
East-West	T1	4	2633	529			800	104			3433	633
		3	2633	529			600	78			3233	607
		2	2633	529			400	52			3033	581
	T2	7	67	14			203	26			270	40
		6	67	14			174	23			241	36
		4	67	14			116	15			183	29
	T3	5	1808	363	1269	165	225	29	82	2	3384	560
		4	1808	363	1015	132	180	23	66	2	3069	521
		3	1808	363	761	99	135	18	49	1	2754	481

Continuing Table 5.13.

Type		Floor	Roof		Facade		Solar protection		Window		Total PV Area in m^2	Total INP in kWp
			Area in m^2	INP in kWp	Area in m^2	INP in kWp	Area in m^2	INP in kWp	Area In m^2	INP in kWp		
East-West	T4	35	147	30	1276	166	1659	216	512	15	3593	426
		34	147	30	1239	161	1612	210	497	15	3495	415
		6	147	30	219	28	284	37	88	3	738	98
	T5	10	706	142	1620	211	600	78			2926	430
		4	706	142	648	84	240	31			1594	257
		3	706	142	486	63	180	23			1372	228
	T6	16	147	30	622	81	400	52	975	29	2144	192
		15	147	30	583	76	375	49	914	27	2019	182
		11	147	30	428	56	275	36	670	20	1520	141
	T7	10	1077	217	1264	164	1238	161	1291	39	4870	580
		4	1077	217	389	51	381	50	397	12	2244	329
		3	1077	217	292	38	286	37	298	9	1952	301
	T8	17	1205	242	3213	418	1700	221			6118	881
		4	1205	242	756	98	400	52			2361	393
		3	1205	242	567	74	300	39			2072	355

Table 5.13: Installed PV area and PV power for each surface in Florianopolis.

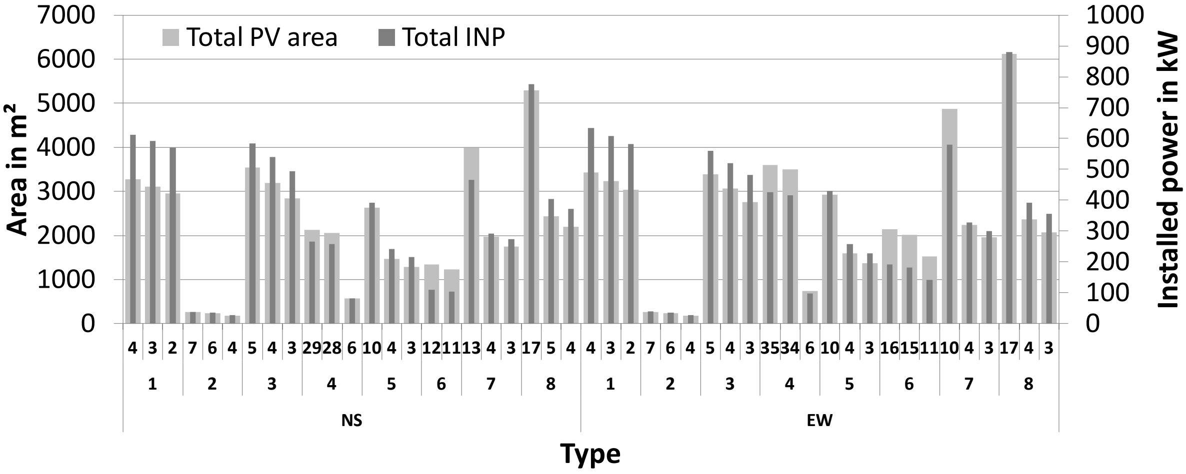
Type		Floor	Roof		Facade		Solar protection		Window		Total PV Area in m^2	Total INP in kWp
			Area in m^2	INP in kWp	Area in m^2	INP in kWp	Area in m^2	INP in kWp	Area in m^2	INP in kWp		
North-South	T1	5	2873	577			1200	156			4073	733
		4	2873	577			960	125			3833	702
		2	2873	577			480	62			3353	640
	T2	7	76	15			266	35			342	50
		6	76	15			228	30			304	45
		4	76	15			152	20			228	35
	T3	5	1932	388	1269	165	450	59	82	2	3733	614
		4	1932	388	1015	132	360	47	66	2	3373	569
	T4	20	164	33	729	95	948	123	292	9	2133	260
		19	164	33	693	90	901	117	278	8	2035	248
		6	164	33	219	28	284	37	88	3	755	101
	T5	10	794	160	1620	211	600	78			3014	448
		6	794	160	972	126	360	47			2126	333
		5	794	160	810	105	300	39			1904	304
	T6	16	162	33	622	81	400	52	975	29	2159	195
		15	162	33	583	76	375	49	914	27	2034	185
		11	162	33	428	56	275	36	670	20	1535	144
	T7	13	1210	243	1264	164	1238	161	1291	39	5002	607
		6	1210	243	583	76	571	74	596	18	2960	411
		5	1210	243	486	63	476	62	497	15	2669	383
	T8	17	1338	269	3213	418	1700	221			6251	908
		6	1338	269	1134	147	600	78			3072	494
		5	1338	269	945	123	500	65			2783	457
East-West	T1	5	2873	577			1200	156			4073	733
		4	2873	577			960	125			3833	702
		2	2873	577			480	62			3353	640
	T2	7	76	15			266	35			342	50
		6	76	15			228	30			304	45
		4	76	15			152	20			228	35

Continuing Table 5.14.

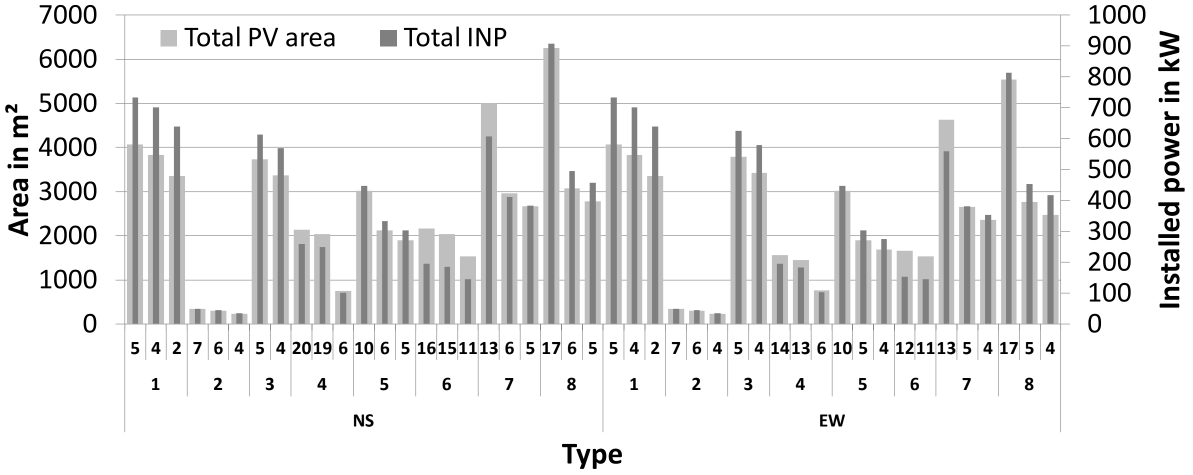
Type		Floor	Roof		Facade		Solar protection		Window		Total PV Area in m²	Total INP in kWp
			Area in m²	INP in kWp	Area in m²	INP in kWp	Area in m²	INP in kWp	Area in m²	INP in kWp		
East-West	T3	5	1985	399	1269	165	450	59	82	2	3786	625
		4	1985	399	1015	132	360	47	66	2	3426	580
	T4	14	176	35	510	66	664	86	205	6	1555	194
		13	176	35	474	62	616	80	190	6	1456	183
		6	176	35	219	28	284	37	88	3	767	103
	T5	10	794	160	1620	211	600	78			3014	448
		5	794	160	810	105	300	39			1904	304
		4	794	160	648	84	240	31			1682	275
	T6	12	161	32	467	61	300	39	731	22	1658	154
		11	162	33	428	56	275	36	670	20	1535	144
	T7	13	1197	241	1264	164	884	115	1291	39	4636	559
		5	1197	241	486	63	476	62	497	15	2656	381
		4	1197	241	389	51	381	50	397	12	2364	353
	T8	17	1323	266	3213	418	1006	131			5542	814
		5	1323	266	945	123	500	65			2768	454
		4	1323	266	756	98	400	52			2479	416

Table 5.14: Installed PV area and PV power for each surface in Fortaleza.

Figure 5.43 summarizes the Tables above and shows the relation between total installed PV area and total installed PV power for each model, orientation and city.



(a)



(b)

Figure 5.43: Relation between total installed PV area and total installed PV power (INP) for different building types in Florianopolis (a) and Fortaleza (b).

Figure 5.44 shows the building types and the maximum and minimum storey number for each one to remain or be a ZEB. The dashed line shows the referential building type height (number of storeys), the gray color represents the efficient buildings and the green shows the zero energy buildings. The letters denote the location and orientation of the models. Letter 'A' is Florianopolis_NS, 'B' is Florianopolis_EW, 'C' is Fortaleza_NS and 'D' is Fortaleza_EW.

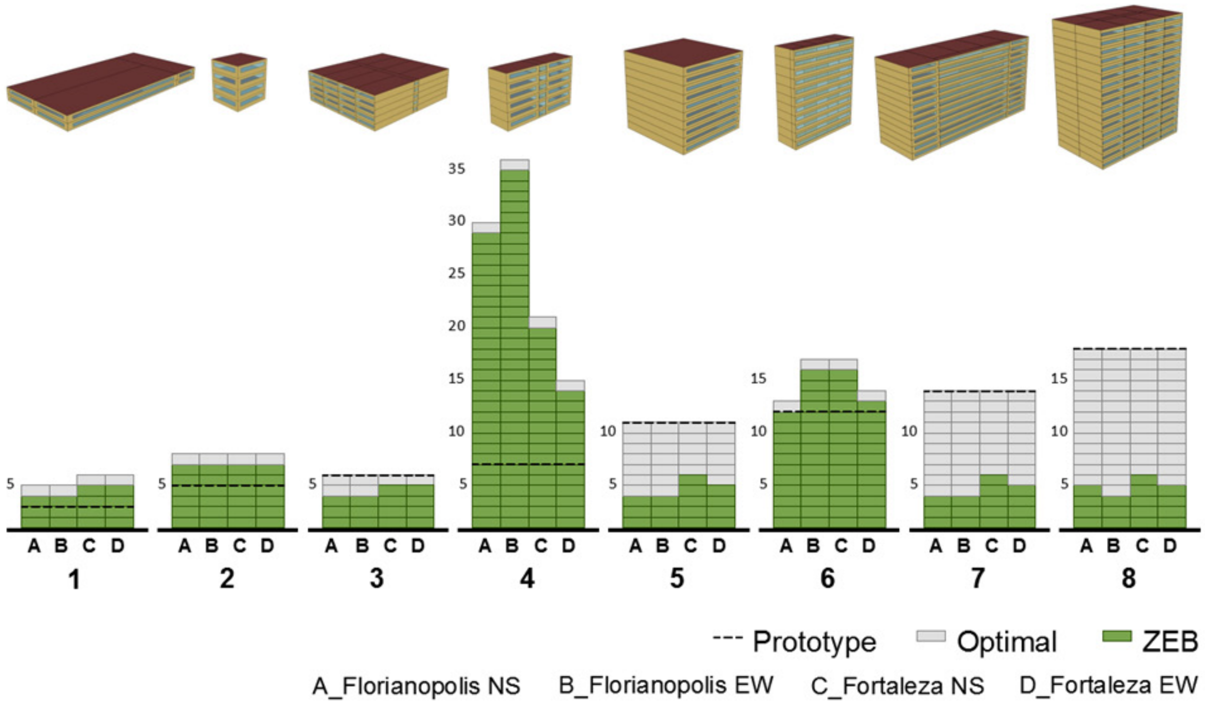
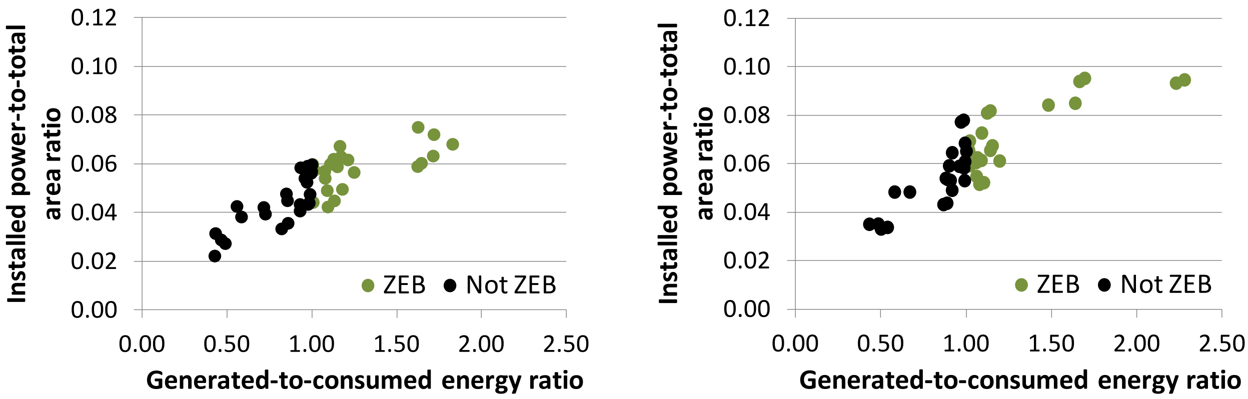


Figure 5.44: Usable number of storeys for ZEB for different types in Florianopolis and Fortaleza.

One result of this analysis is the insight that the relationship between building energy consumption, generated energy and building height is linear. The more storeys are added with PV modules, the more energy is generated and used. Most of the building types can reach ZEB until three storeys in Florianopolis and four storeys in Fortaleza. T4 and T5 types, which have a similar volumetry, are the models that remain ZEB even with an extended number of storeys, showing their high potential as ZEB type and contradictioning the theory that only small buildings can reach ZE status.

The ratio between installed power and total area (y-axis) of generated to consumed energy (x-axis) is presented in Figure 5.45. The green dots in the graphic stand for ZEB volumetries and the black dots for non ZEB volumetries. The correlation of the models give a R^2 of 0.66 for Florianopolis and a R^2 of 0.73 for Fortaleza, which can be seen in Apendice A.6, as well as the equation and the energy demand and generation for all simulated models.

This figure comprises all 94 combinations, resulting from the eight types (T1-T8), for two cities (Florianopolis and Fortaleza) and two orientations (North-South and East-West). A detailed description of the models is given in Table 5.13 and Table 5.14.



(a) (b)

Figure 5.45: Installed power to total area ratio and generation to consumed energy ratio for Florianopolis (a) and Fortaleza (b).

The cities show different ranges for ZEBs type. In Florianopolis all evaluated buildings with an installed power to total area ratio higher than 0.06 are ZEB and there is no ZEB with a ratio below 0.04. While in Fortaleza all ZEBs have a ratio above 0.08 and there is no ZEB with a ratio below 0.05. For Fortaleza more installed power was necessary to reach ZEB. For both cities, it was easier to transform the compact volumetries such as T1 and T2, showing the highest ratios, into ZEB. In contrast, the large ZEB types (T5, T7, and T8), have the lowest ratios. Regarding all models simulated within this work for Florianopolis a ratio of at least 0.04 is necessary to achieve a ZEB and buildings with a ratio above 0.06 are most likely ZEBs. For Fortaleza the ratios are 0.05 and 0.08 respectively.

5.2.6 Summary of the analysis

In this section the transformation of standard Brazilian office buildings into a net zero energy buildings was presented. Therefore in a first step a methodology for energy reduction was developed using one representative office building type. Afterwards, PV modules were applied to reach an equalized energy balance. The concept was then applied to different building types. The transformation was made for two cities with different climate mainly focusing on solar technology application, considering the building heat gain, solar irradiation and daylighting availability.

The two climates required different design concepts for the reduction of the energy consumption and for energy generation. In Fortaleza although more energy was generated, more photovoltaic modules were necessary for a zero energy building due to the higher total energy consumption, mainly caused by air-conditioning. The subtropical climate of Florianopolis requires less installed PV modules due to its lower total energy consumption in comparison to the tropical climate of Fortaleza.

The semi-transparent PV windows turned out to be an interesting option as a replacement for traditional windows in hallways since they contributed with 21 % of the generated electricity – though the used modules have an efficiency of only 3 %.

From the transformation of different office building types into ZEB it was possible to analyze the potential of different volumetries and the relationship between envelope area and net floor area on the energy balance. The study confirmed that compact building types are transformed more easily into ZEB than high-rise buildings, however exceptions exist and it is not only the height of the building that will define its potential to be a ZEB.

The load matching and grid interaction analysis show different index values depending on the time period. It seems a good method for high resolution analysis considering on-site generation and grid interaction exchanges, which can be relevant in the future.

5.3 Influence of the urban context on the solar irradiation

As the ZE buildings developed above strongly depend on electricity generation from solar energy it is crucial to consider the buildings' surroundings for a more realistic simulation. Accordingly, the influence of shading from the surrounding buildings on the PV energy generation was investigated and its results are discussed in this section. Within the simulations two main points were investigated. First, a study was made to define the minimum level of solar irradiation on the surface for application of PV modules. Second, the influence of shading on energy generation of the examined building types was determined. The building types with PV modules applied as in the section of the nZEB development were used as reference models and compared to the results obtained with the new application of PV models according to the solar irradiation results.

5.3.1 Solar irradiation on the building envelope

The average solar irradiation for each surface without surrounding for Florianopolis and Fortaleza are presented in Figure 5.46. Both cities have low geographic latitudes: Florianopolis 27° and Fortaleza 3°. Thus the solar elevation angle is big throughout the year which results in a large difference between the irradiation on the roof and the facade.

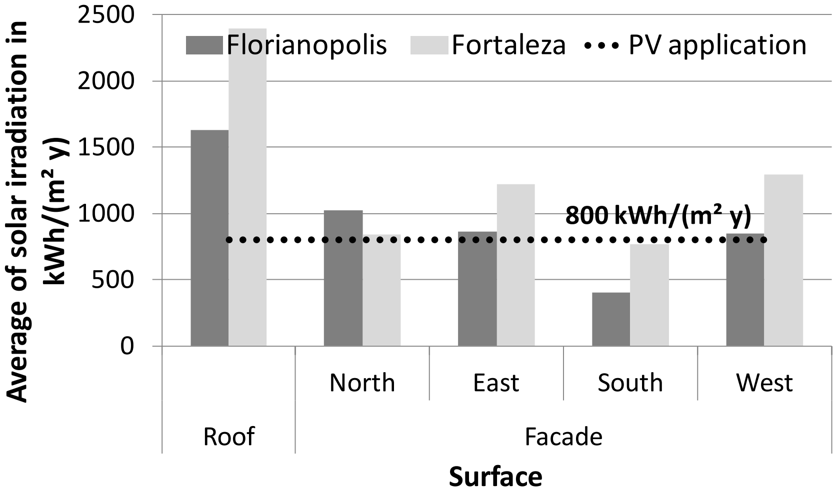


Figure 5.46: Average[13] solar irradiation levels on surfaces without surrounding (reference).

As the results shown in the Figure 5.46 present the achievable maximum irradiation for each facade they can be used for a comparison with the results obtained with surrounding. For the roof and all orientations always two columns are shown, one for each city. The lines

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[13] Average of all measured points on a surface.

represent the minimal required solar irradiation for an application of PV modules on that surface.

For both cities a minimum solar irradiation of 800 kWh/(m^2 y) was required for application of PV modules. The roof is the surface with the highest solar irradiation of the building. The facades receive considerably lower irradiation values, varying with the orientation. East and West oriented facades receive similar values in both cities with around 50 % of the irradiation on the roof. The biggest differences appear for the North and South orientations. Florianopolis has around 25 % more solar irradiation than Fortaleza on the North facade.

The results of the solar irradiation considering the surrounding for all surfaces, types and cities are presented in Appendix A.7. Using this data the storeys with PV application for each building type and city were defined. Table 5.15 and Table 5.16 show where PV modules can be used for uniform and random urban layout with the main facade oriented North-South and East-West, respectively. The storeys where PVs were applied are denoted by two numbers, for example, 4_3 means that PVs were applied on the facade from the 3rd to the 4th floor.

City	**Florianopolis_North-South**						**Fortaleza_North-South**					
Type	**Urban context**	**Roof**	**Storey level**				**Urban context**	**Roof**	**Storey level**			
			N	**E**	**S**	**W**			**N**	**E**	**S**	**W**
T1	0	y	2 _1	2_1	-	2_1	0	y	2_1	2_1	-	2_1
	8	y	2_1	-	-	-	6	y	-	2_1	-	2_1
T2	0	y	4	-	-	-	0	y	-	4_3	-	4_3
	3	y	-	-	-	-	3	y	-	-	-	4
T3	0	y	5_1	5	-	5	0	y	5	5_1	-	5_1
	8	y	5_1	-	-	-	6	y	-	5_1	-	5_1
T4	0	y	6	-	-	-	0	y	-	6_4	-	6_4
	3	y	-	-	-	-	3	y	-	-	-	6_3
T5	0	y	10_8	-	-	-	0	y	-	10_7	-	10_7
	8	y	10_5	-	-	-	3	y	-	10_4	-	10_1
T6	0	y	11	-	-	-	0	y	-	11_10	-	11_9
	3	y	11_9	-	-	-	3	y	-	-	-	11_3
T7	0	y	13_11	-	-	-	0	y	-	13_8	-	13_8
	3	y	13_6	13	-	13	6	y	-	13_2	-	13_2
T8	0	y	17_15	-	-	-	0	y	-	17_14	-	17_14
	3	y	17_5	17_11	-	17_10	3	y	17_11	17_6	-	17_1

Table 5.15: Summary of PV application surfaces according to solar irradiation levels for buildings with main facades oriented to North-South.

City	Florianopolis_East-West						Fortaleza_East-West					
Type	Urban context	Roof	Storey level				Urban context	Roof	Storey level			
			N	L	S	O			N	L	S	O
T1	0	y	2 _1	2_1	-	2_1	0	y	2_1	2_1	-	2_1
	8	y	2_1	-	-	-	6	y	-	2_1	-	2_1
T2	0	y	4	-	-	-	0	y	-	4_3	-	4_3
	3	y	-	-	-	-	3	y	-	-	-	4
T3	0	y	5_1	5	-	5	0	y	5	5_1	-	5_1
	8	y	5_1	-	-	-	6	y	-	5_1	-	5_1
T4	0	y	6_5	-	-	-	0	y	-	6_5	-	6_5
	3	y	-	-	-	-	3	y	-	-	-	6_4
T5	0	y	10_8	-	-	-	0	y	-	10_7	-	10_7
	8	y	10_5	-	-	-	3	y	-	10_4	-	10_1
T6	0	y	11_10	-	-	-	0	y	-	11_10	-	11_10
	3	y	-	-	-	-	3	y	-	-	-	11_4
T7	0	y	13_10	-	-	-	0	y	-	13_9	-	13_9
	3	y	13_7	-	-	13_9	6	y	-	13_4	-	13_4
T8	0	y	17_15	-	-	-	0	y	-	17_14	-	17_14
	3	y	17_5	17_12	-	17_7	6	y	17_16	17_1	-	17_1

Table 5.16: Summary of PV application surfaces according to solar irradiation levels for buildings with main facades oriented East-West.

5.3.2 Influence of shading on building surfaces

Shading influences the energy balance of a building in two ways. One is the energy consumption for cooling and lighting, which can increase or decrease with the heat gain / loss through the envelope. Another one is the energy generation by the PV panels, where shading on the modules reduces electricity production.

Buildings with a surrounding consume up to 5 % less annual energy, compared to buildings without surrounding. The results for the eight types for North-South and East-West orientations in Florianopolis and Fortaleza are presented in Figure 5.47. Types T2, T4 and T6 are the ones with the highest consumption reduction between 1.5 % and 5 %, depending on the orientation. The other types achieve a reduction of less than 1 % of the annual energy consumption. But considering the high electricity consumption value, 1 % is a significant amount of energy. The orientation that provides highest reductions is East-West for both cities the reduction is almost the same for all building types.

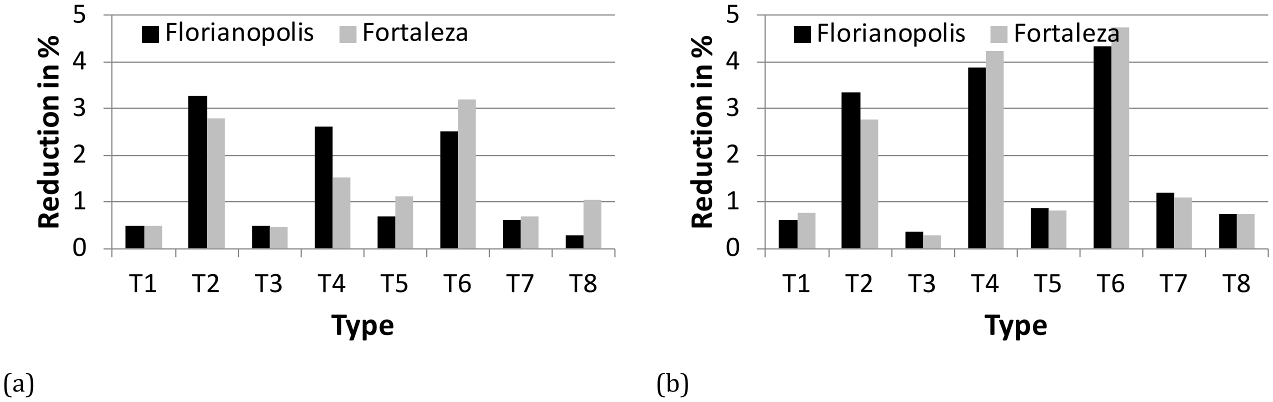


Figure 5.47: Average reduction of the energy consumption for all types with surrounding for North-South (a) and East-West (b) oriented main facade.

5.3.2.1 Influence of shading on electricity generation

In this section the influence of shading on the generated energy is presented for each building type. In the figures below the columns show the generated energy, where: column 'T' in black is the electricity of the reference building type without surrounding; column 'Uni' in light gray is the electricity for the uniform height urban layout; and column ‘Avg’ in dark gray is the average generated electricity of all (#1-#10) random urban layouts. The column ‘Max’ is the maximum generated electricity of all (#1-#10) random urban layouts; and the column ‘Min’ is the minimum generated electricity of all (#1-#10) random urban layouts. The black dots show the energy consumption of the referential building type (T).

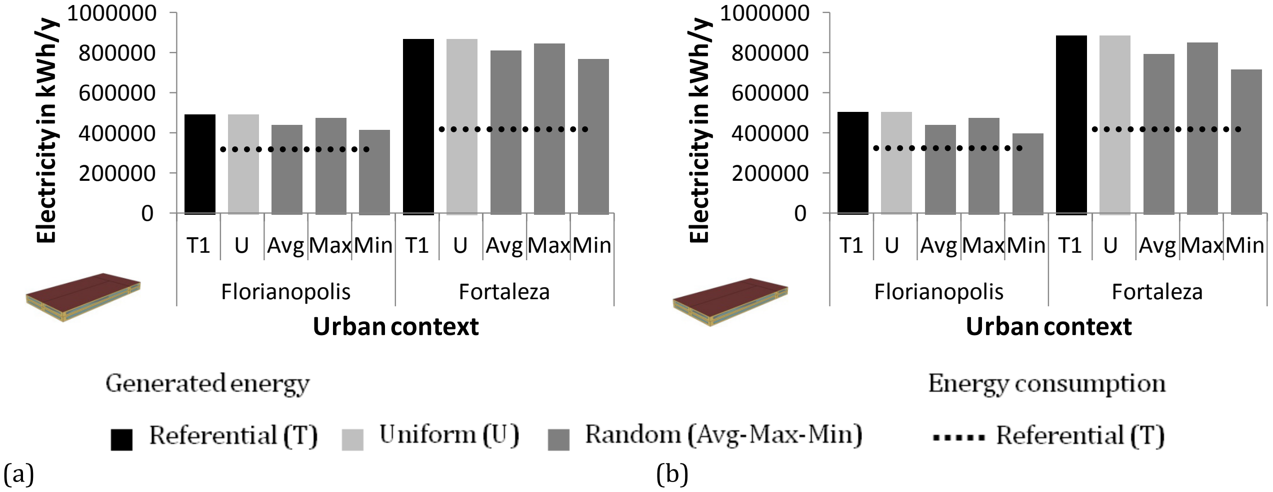
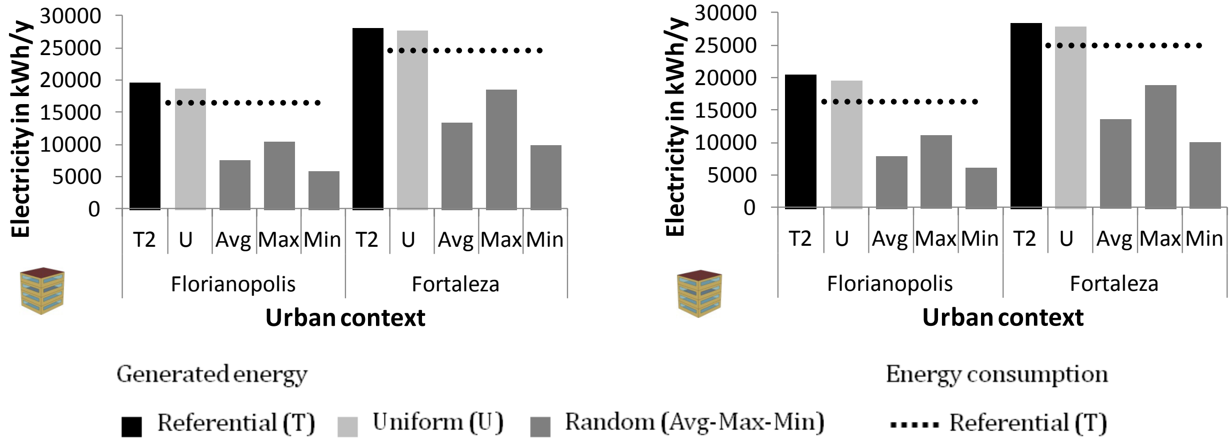
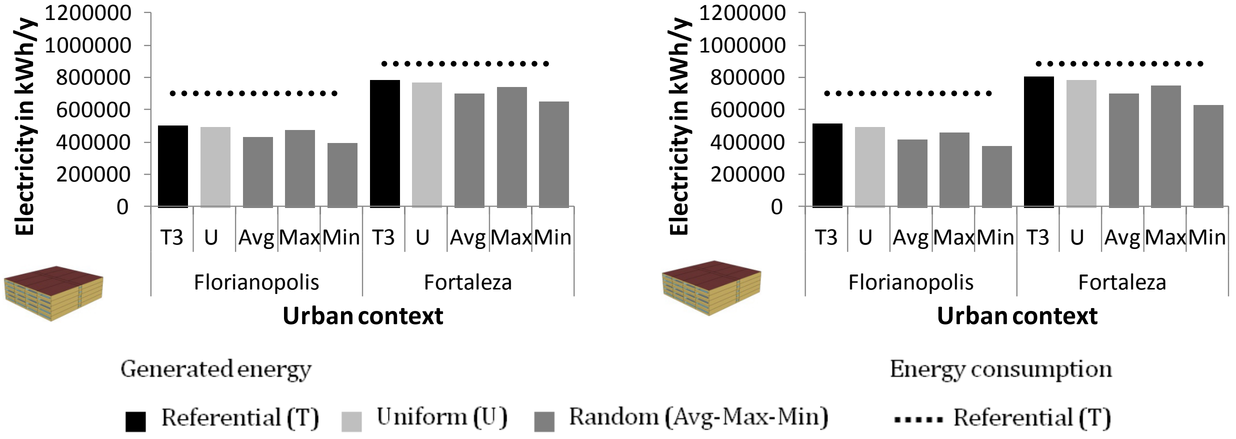


Figure 5.48: Generated energy for T1 with surrounding for North-South (a) and East-West (b) orientations in Florianopolis and Fortaleza.



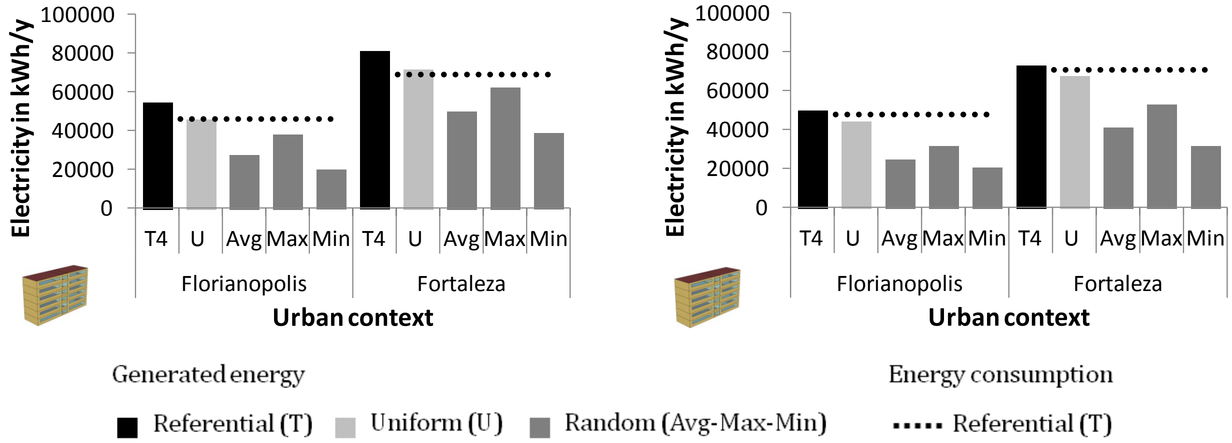
(a) (b)

Figure 5.49: Generated energy for T2 with surrounding for North-South (a) and East-West (b) orientations in Florianopolis and Fortaleza.



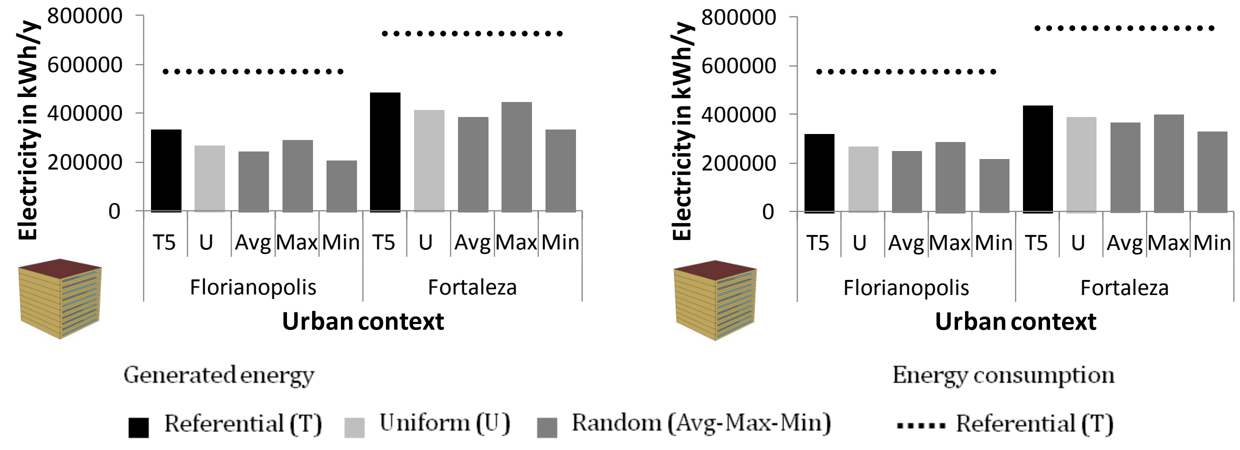
(a) (b)

Figure 5.50: Generated energy for T3 with surrounding for North-South (a) and East-West (b) orientations in Florianopolis and Fortaleza.



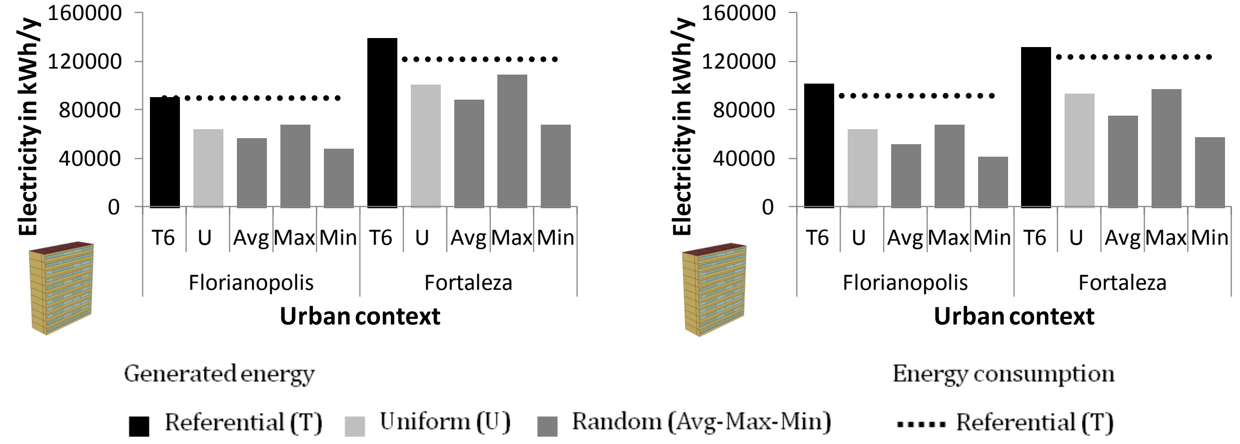
(a) (b)

Figure 5.51: Generated energy for T4 with surrounding for North-South (a) and East-West (b) orientations in Florianopolis and Fortaleza.



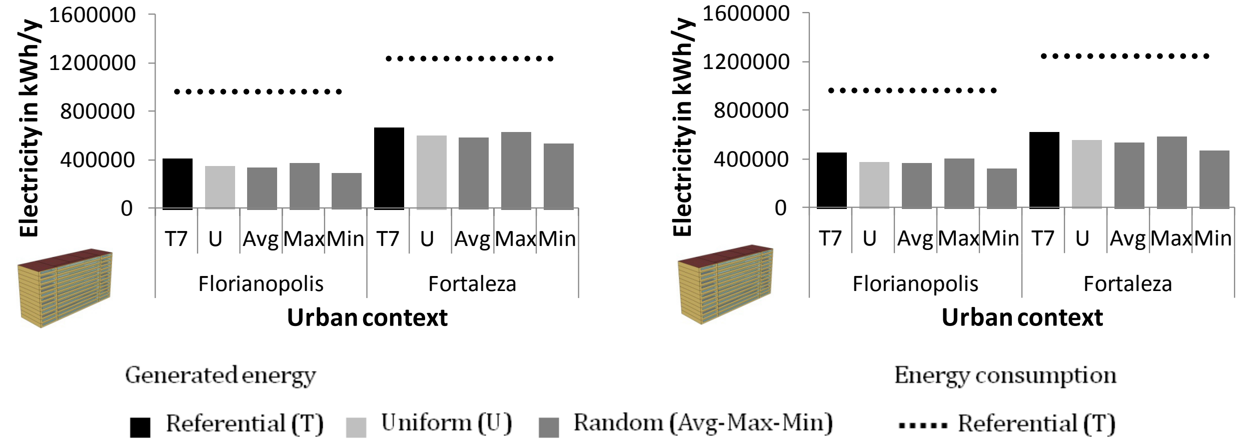
(a) (b)

Figure 5.52: Generated energy for T5 with surrounding for North-South (a) and East-West (b) orientations in Florianopolis and Fortaleza.



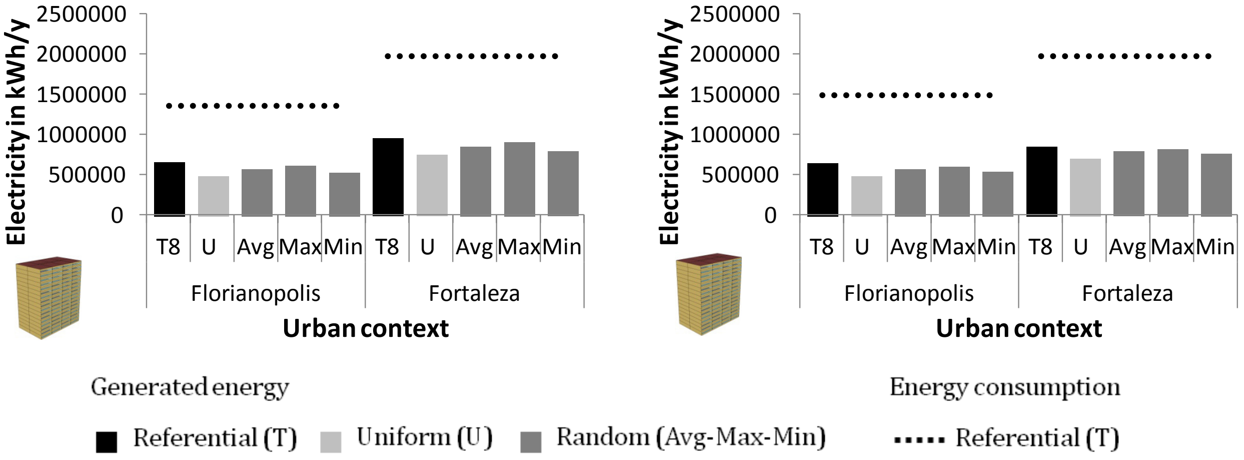
(a) (b)

Figure 5.53: Generated energy for T6 with surrounding for North-South (a) and East-West (b) orientations in Florianopolis and Fortaleza.



(a) (b)

Figure 5.54: Generated energy for T7 with surrounding for North-South (a) and East-West (b) orientations in Florianopolis and Fortaleza.



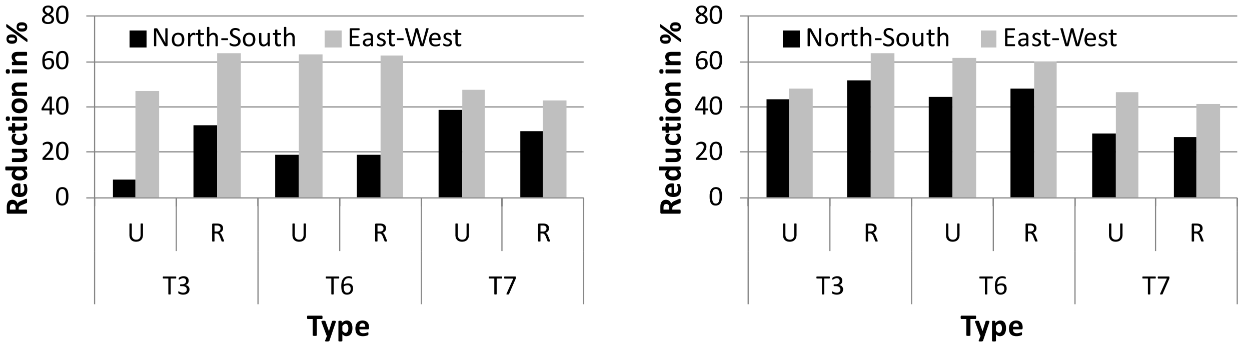
(a) (b)

Figure 5.55: Generated energy for T8 with surrounding for North-South (a) and East-West (b) orientations in Florianopolis and Fortaleza.

According to the results showed above, 50 % of the building types generated more energy in the uniform urban layout, because the roof installed PVs were not shaded. These types are the lower ones with a maximum of six storeys and few PV installed on the envelope in comparison to the high-rise buildings types. They generated almost the same amount of electricity as the models without surrounding, with exception of T4.

The high-rise building types with 10 to 17 storeys generated less electricity than the equivalent models without surrounding, however, the maximum ('Max') energy generation with random urban layout is higher than the uniform layout. Only type T8, with 17 storeys, has a higher average generated energy in random layout than the uniform. It seems that the uniform layout is better for buildings with few storeys, where most of PVs are applied on the roof, but for high-rise buildings with a high amount of PVs installed on the facade the random layout shows a better performance.

In Figure 5.56 is possible to observe the reduction of the generated energy with shading on the PV windows. This reduction changes from 10 % to 60 % depending on the building type, city and orientation. In general, in Fortaleza higher reduction values can be observe than in Florianopolis and the East-West orientation shows the highest loss of generated energy due to shading for both cities.



(a) (b)

Figure 5.56: Reduction of the PV window generated energy with surrounding for uniform (U) and average random (R) layouts in Florianopolis (a) and Fortaleza (b).

5.3.2.2 New PV application on building envelope

The new application of PV modules on the envelope according to the solar irradiation on the surfaces respecting the influence of the surrounding is presented in Table 5.17 for Florianopolis and in Table 5.18 for Fortaleza. The tables show the PV application for all building types, cities and orientation, as well as, for the uniform urban layout (#0) and selected random layouts (#1 to #10) for each building type. The gray color marks surfaces and orientations with PV application and the numbers are the storeys where PVs were applied, as in Tables 15 and 16.

Type	**Urban Context**	**Roof**	**Facade**				**Solar Protection**				**Window**
			N	**E**	**S**	**W**	**N**	**E**	**S**	**W**	
T1_NS	0	▨									
	8	▨					4				
T2_NS	0	▨									
	3	▨									
T3_NS	0	▨	5_1					5		5	5_1
	8	▨	5_1								5_1
T4_NS	0	▨					6				
	3	▨									
T5_NS	0	▨					10_8				
	8	▨					10_5				
T6_NS	0	▨									11
	3	▨									11_9
T7_NS	0	▨					13_11				13_11
	3	▨		13		13	13_6				13_6
T8_NS	0	▨					17_15				
	3	▨		17_11		17_10	17_5				
T1_EW	0	▨									
	8	▨									
T2_EW	0	▨					4				
	3	▨									

Continuing Table 5.17.

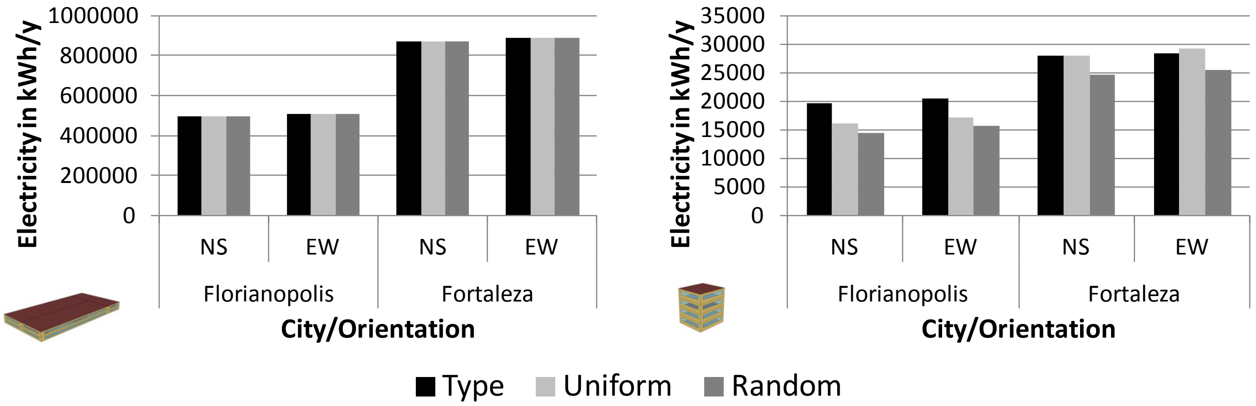
Type	Urban Context	Roof	Facade				Solar Protection				Window
			N	E	S	W	N	E	S	W	
T3_EW	0	▨					5_1				
	8	▨		5		5	5_1				5
T4_EW	0	▨	6_5								
	3	▨									
T5_EW	0	▨	10_8								
	8	▨	10_5								
T6_EW	0	▨	11_10								
	3	▨									
T7_EW	0	▨	13_10								
	3	▨	13_7							13_9	13_9
T8_EW	0	▨	17_15								
	3	▨	17_5					17_12		17_7	

Table 5.17: PV re-application for each building type and case in Florianopolis for different urban contexts.

Type	Urban Context	Roof	Facade				Solar Protection				Window
			N	E	S	W	N	E	S	W	
T1_NS	0	▨									
	6	▨									
T2_NS	0	▨						4_3		4_3	
	3	▨								4	
T3_NS	0	▨	5					5_1		5_1	5
	6	▨						5_1		5_1	
T4_NS	0	▨		6_4		6_4					
	3	▨				6_3					
T5_NS	0	▨		10_7		10_7					
	3	▨		10_4		10_1					
T6_NS	0	▨		11_10		11_9					
	3	▨				11_3					
T7_NS	0	▨		13_8		13_8					
	6	▨		13_2		13_2					
T8_NS	0	▨		17_14		17_14					
	3	▨		17_6		17_1	17_11				
T1_EW	0	▨									
	6	▨									
T2_EW	0	▨						4_3		4_3	
	3	▨								4	
T3_EW	0	▨		5_1		5_1	5				5_1
	6	▨		5_1		5_1					5_1
T4_EW	0	▨						6_5		6_5	
	3	▨								6_4	
T5_EW	0	▨						10_7		10_7	
	3	▨						10_4		10_1	
T6_EW	0	▨						11_10			11_10
	3	▨									11_4
T7_EW	0	▨						13_9		13_9	13_9
	6	▨						13_4		13_4	13_4
T8_EW	0	▨						17_14		17_14	
	6	▨	17_16					17_1		17_1	

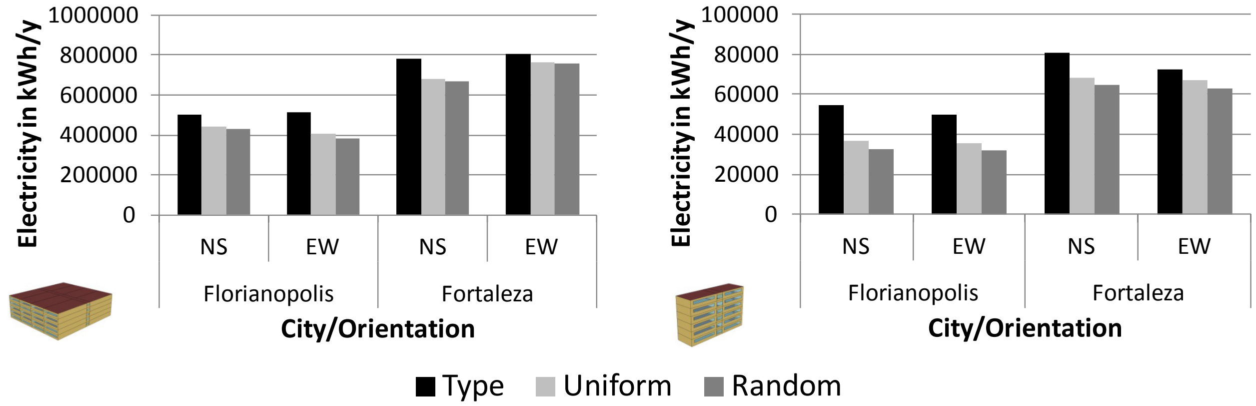
Table 5.18: PV re-application for each building type and case in Fortaleza for different urban contexts.

The results of generated energy without surrounding of the reference building type, which is the one where PV was applied without considering shading (in black), the new application for the uniform urban layout (in light gray) and for the best random urban layout (in dark gray) are presented in the figures below.



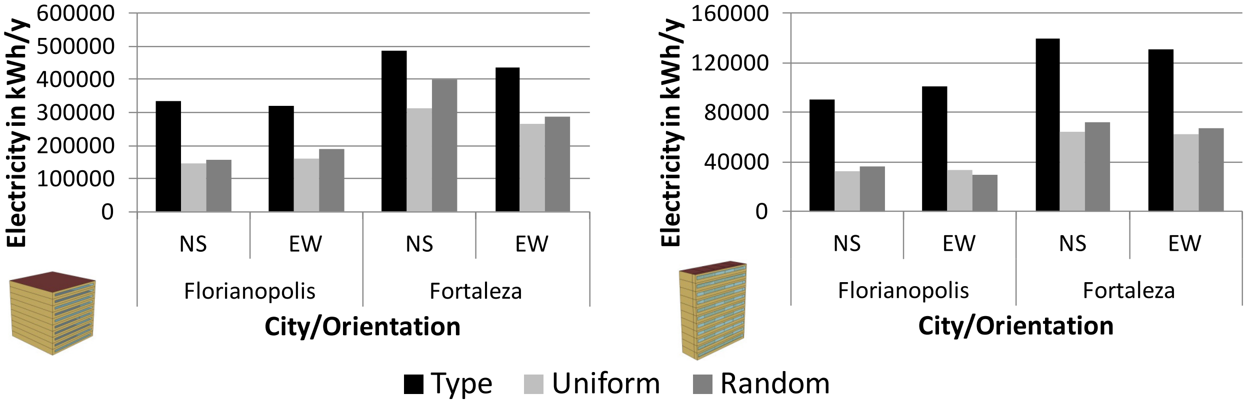
(a) (b)

Figure 5.57: Generated electricity for new PV application without surrounding for T1 (a) and T2 (b) types in Florianopolis and Fortaleza for North-South (NS) and East-West (EW) orientations.



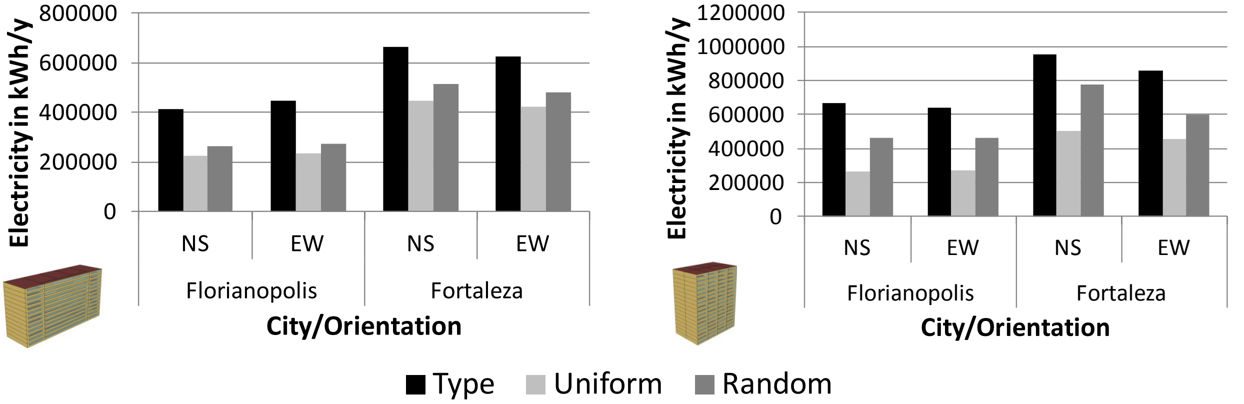
(a) (b)

Figure 5.58: Generated electricity for new PV application without surrounding for T3 (a) and T4 (b) types in Florianopolis and Fortaleza for North-South (NS) and East-West (EW) orientations.



(a) (b)

Figure 5.59: Generated electricity for new PV application without surrounding for T5 (a) and T6 (b) types in Florianopolis and Fortaleza for North-South (NS) and East-West (EW) orientations.



(a) (b)

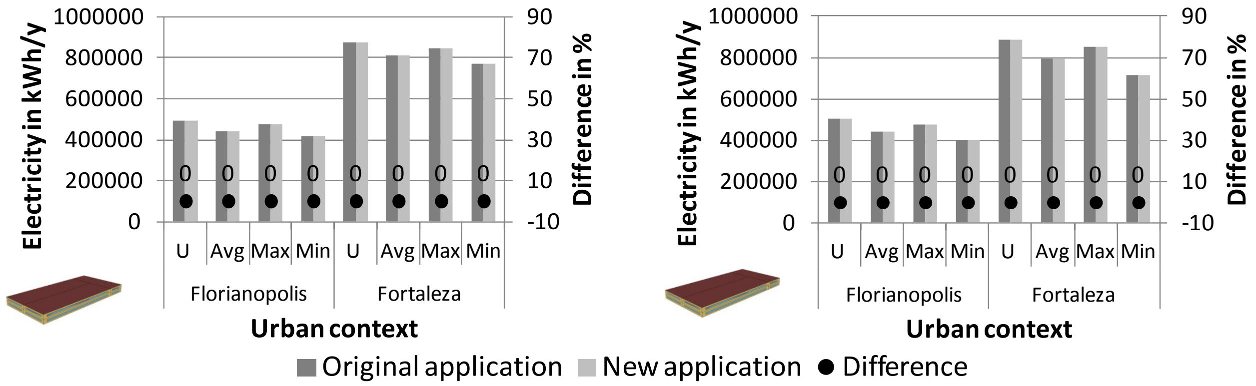
Figure 5.60: Generated electricity for new PV application without surrounding for T7 (a) and T8 (b) types in Florianopolis and Fortaleza for North-South (NS) and East-West (EW) orientations.

For most of the building types less PV modules were applied on the envelope in the random layout than were for the reference building type. This reduction of PV module is due to the low solar irradiation level on the surface. Despite energy can also be generated by low irradiation, the price of the modules is still high and the payback would not compensate an installation.

For type T1 the PV application remained the same for the three cases, since PV modules are applied only on the roof. For the types T2, T3 and T4, the medium height building types, more PVs are applied on the roof than on the facade. The roof is the surface with the highest solar irradiation. This explains the highest values of generated energy for the uniform urban layout. For T2 in Fortaleza the uniform urban layout generates more electricity than the reference building type because the PV modules were applied on surfaces with high solar irradiation values. For the high-rise building types with a high amount of PV installed on the vertical surfaces, random layout presents higher values as the uniform layout.

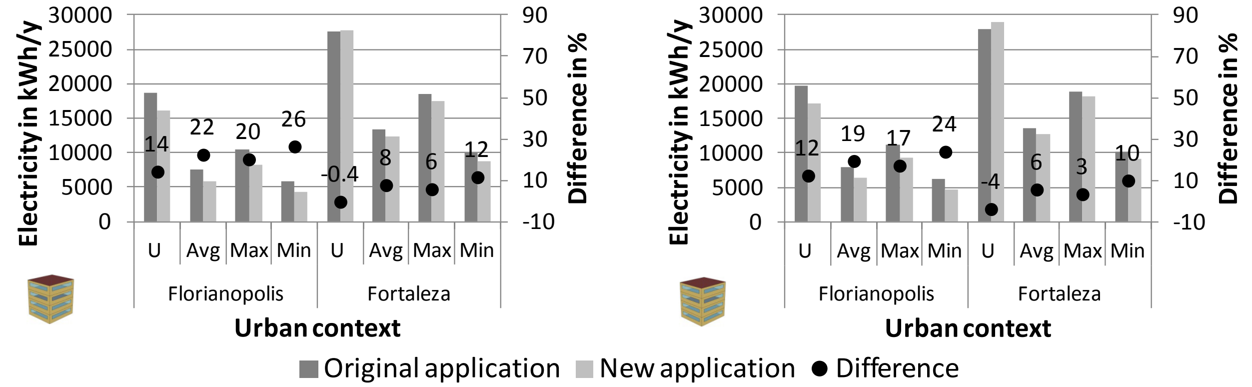
5.3.2.3 Simulation results with new applied PVs in the urban context

The influence of shading on the generated energy for the building types with newly applied PVs was evaluated and the results are presented and discussed in this subsection. The figures below present the results obtained for the uniform and random urban layouts for the models with original PV application (reference) and the models with new PV application (considering solar irradiation levels) for comparison. The generated energy is represented by the columns and the black dots show the reduction of the generated energy between original and new application.



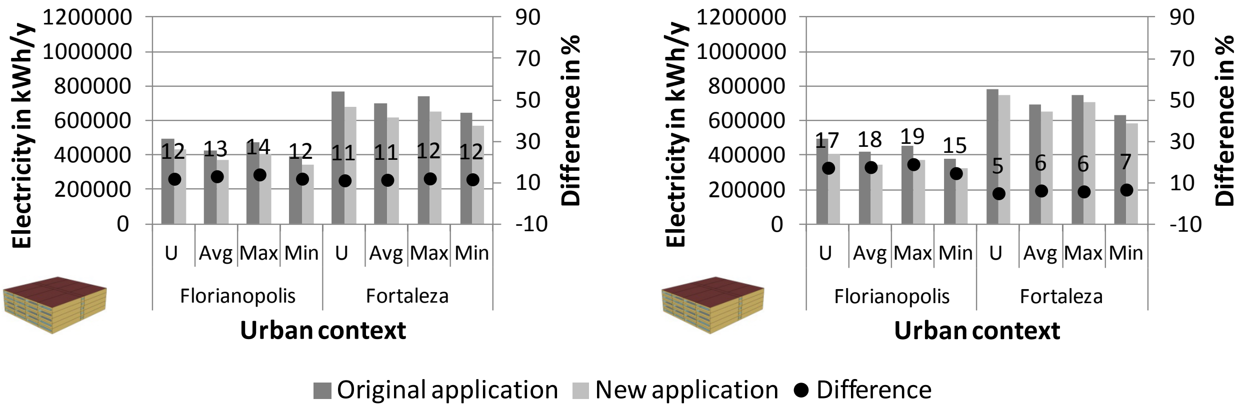
(a) (b)

Figure 5.61: Generated energy of original and new PV application for T1 North-South (a) and East-West (b) orientations; the difference value is the percental reduction of the generated energy.



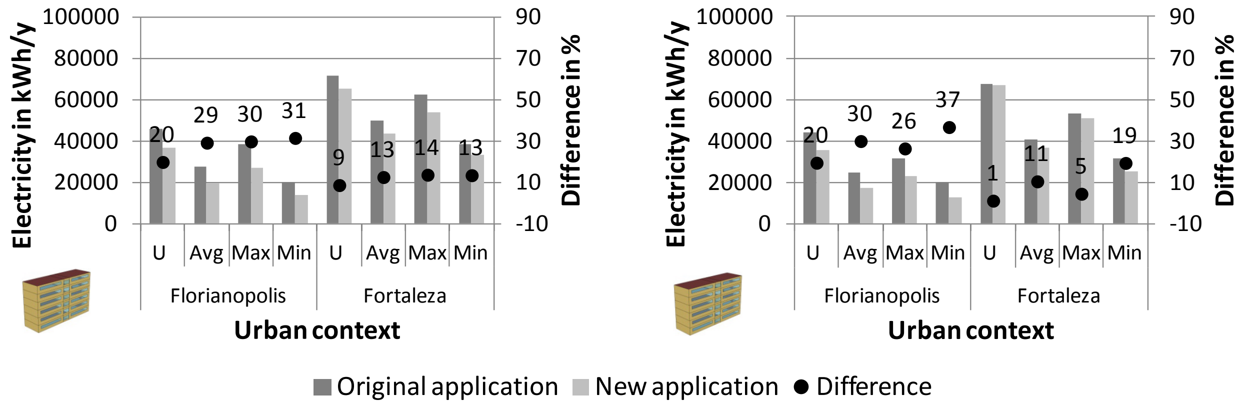
(a) (b)

Figure 5.62: Generated energy of original and new PV application for T2 North-South (a) and East-West (b) orientations; the difference value is the percental reduction of the generated energy



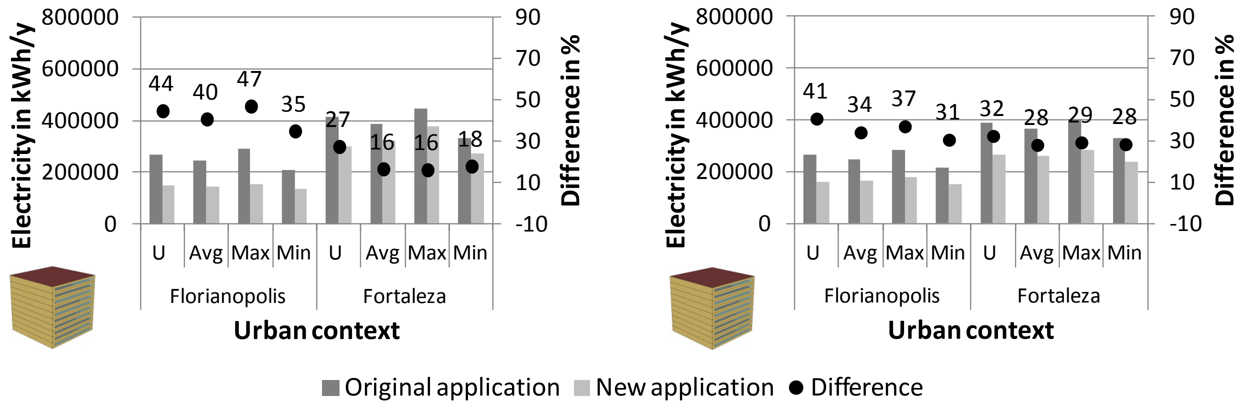
(a) (b)

Figure 5.63: Generated energy of original and new PV application for T3 North-South (a) and East-West (b) orientations; the difference value is the percental reduction of the generated energy



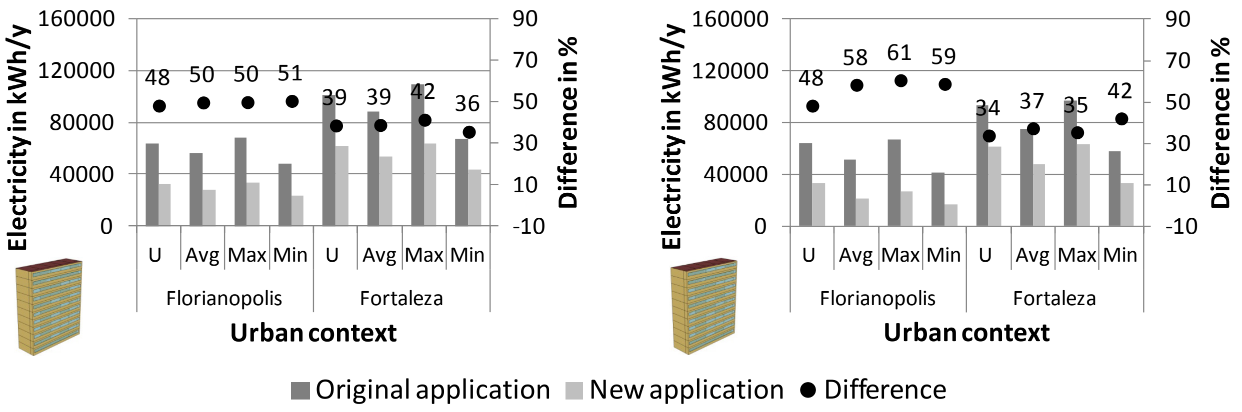
(a) (b)

Figure 5.64: Generated energy of original and new PV application for T4 North-South (a) and East-West (b) orientations; the difference value is the percental reduction of the generated energy



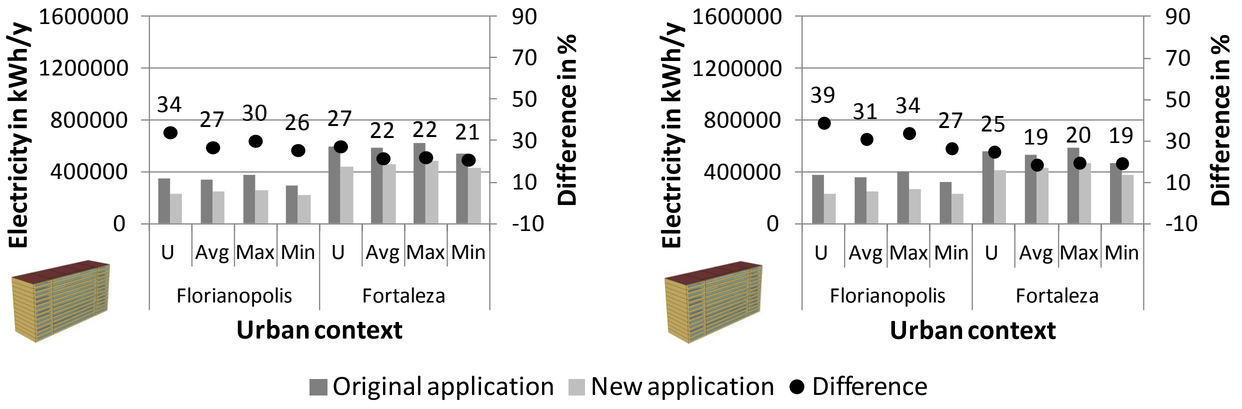
(a) (b)

Figure 5.65: Generated energy of original and new PV application for T5 North-South (a) and East-West (b) orientations; the difference value is the percental reduction of the generated energy



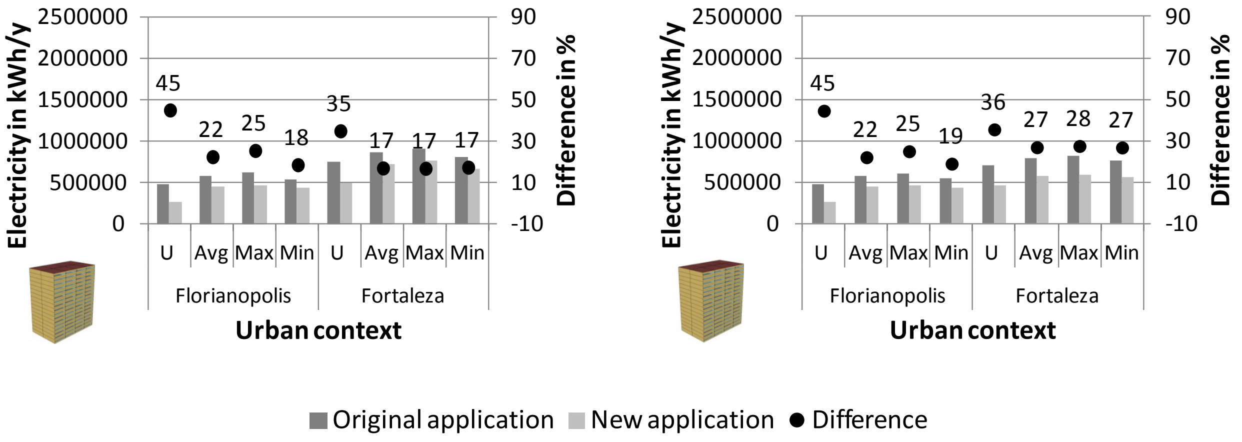
(a) (b)

Figure 5.66: Generated energy of original and new PV application for T6 North-South (a) and East-West (b) orientations; the difference value is the percental reduction of the generated energy



(a) (b)

Figure 5.67: Generated energy of original and new PV application for T7 North-South (a) and East-West (b) orientations; the difference value is the percental reduction of the generated energy



(a) (b)

Figure 5.68: Generated energy of original and new PV application for T8 North-South (a) and East-West (b) orientations; the difference value is the percental reduction of the generated energy

As expected, all building types with newly applied PVs have generated less energy than the models with PV application without regarding the solar irradiation levels. The reduction varies between 12 % and 61 % in Florianopolis and 1 % to 42 % in Fortaleza. The exception is T2 in Fortaleza, where PV modules on the North oriented solar protection were placed on the East orientated ones, generating 4 % more electricity for the East-West oriented model and 0.4 % for the North-South oriented model. For T1 no differences occur, since the module has PV installed only on the roof for both cases.

5.3.3 Summary of the analysis

This section presented the influence of the shading caused by the urban context on the building envelope. The shading influences the energy consumption for cooling and lighting, since less solar irradiation reaches the building reducing the cooling load and increasing the required artificial lighting. However, regarding the annual energy balance, a reduction up to 5 % of the building electricity demand can be obtained. The shading also reduces the generated energy by PV modules applied on the envelope.

The influence is different for the uniform and random urban layouts. Building types with medium height (until 6 storeys) with more PV installed on the roof, generated more energy in an uniform urban layout, while for high-rise types with many PV modules installed on vertical surfaces, the random urban layout, where the surrounding buildings have at most the same height is favorable. The separation between buildings (width of the street) is also a significant factor for the assessment of solar irradiation on the building's surfaces.

The defined minimal solar irradiation level for PV application, can change according to PV installation costs and technical limitations. Also different values for roof and facades can be meaningful [33], since BIPV applications can reduce costs by substituting other materials or as the PV modules are used for aesthetic reasons. Finally, only types T1 and T2 remain ZEB when inserted in an urban context with the original or new PV application. However, for T2 model only in the uniform urban layout.

6 Conclusions

The present work investigated possibilities for the transformation of typical Brazilian office buildings into zero energy buildings using established energy consumption reduction methods and photovoltaic technologies, especially the new technology of semi-transparent PV windows, which is an important contribution to ensure the energy supply in the country as the building sector is one of the main energy consumers. This gets even more important with the increasing middle-class, further raising the buildings' energy demand, which will be hardly satisfiable by conventional energy sources. Therefore technologies for the reduction of the energy use in buildings, together with new energy sources must be used. Applying these technologies buildings' envelopes can be enhanced to not only reduce the energy consumption but also generate energy.

For the methodic transformation of typical Brazilian office buildings into zero energy buildings the approach was divided into two main tasks. At first the reduction of the energy consumption and second the application of renewable energy sources, in this case PV technology. For an optimal use of PV technology a detailed research on the new technology of semi-transparent PV windows was done. Additionally, a volumetric analysis of different building types, the interaction with the local energy grid and the influence of the urban environment were carried out.

From a literature review a set of typical Brazilian office buildings with different volumetries were defined. The different volumetries made a broader evaluation of the developed strategies for the reduction of energy consumption, as well as the application of PV technology, considering the available surfaces on the envelope, possible.

For the study mainly two computer programs were used: EnergyPlus and Daysim/Radiance. EnergyPlus is a useful tool for building energy performance analysis in combination with BIPV installations. The combination of EnergyPlus and Daysim allows an integrated simulation including daylight analyses by calculating the annual energy consumption with EnergyPlus, using the data created by Daysim. However, to evaluate semi-transparent PV windows some adaptations were necessary. Semi-transparent PV windows cannot be simulated directly with EnergyPlus, so the generated electrical energy has to be calculated using a spreadsheet program.

The analysis of the semi-transparent PV window technology revealed that due to the low visible transmittance of the semi-transparent PV existing on the market today, their application is recommended only for places with low required illuminance levels and short permanency. Examining the relationship between transmittance and efficiency of the semi-transparent PV cells, it was found that the efficiency has a higher influence on the energy balance. However, semi-transparent PVs can be an interesting element for high-rise buildings as they had a significant contribution to the generated energy in suitable cases. The heat balance analysis showed that the biggest disadvantage of the semi-transparent PV windows is the additional heat produced by the PV cells, which can reach values around 70 °C. This temperature level can be a serious hazard for users or cause other types of risks.

The results obtained in the process of transforming typical Brazilian office buildings into ZEBs showed, that the actual recommendations of the Brazilian labeling program are quite effective but not sufficient. Further reductions are possible applying technologies commonly used in other climates, such as double glazing windows, low-E glasses, insulation of the exterior walls and interior windows to improve daylight availability. Further the evaluation of the results obtained for the two cities, showed, that the applied methods, e.g. the use of PV windows must be reviewed critically in the context of the local climate and building orientation.

The investigation of the various building types revealed that the number of storeys does not limit a building to be a ZEB. The relationship between installed power and total area can within certain boundaries serve as an indicator to test the suitability of a building type for a ZEB. Some high-rise types showed a high potential to be ZEBs due to the available envelope surface for PV application. Anyway, buildings with few storeys, where the roof is the main surface for PV application, are more likely to serve as ZEB types. Another important result is the importance of high resolution load and grid matching analyses. They show which renewable energy sources are suitable for a building and what influence on the local energy grid has to be expected. Currently used longer period analyses only give a more general relationship between the used and generated energy, but the actual interaction with the energy grid cannot be examined.

The last part was the evaluation of the influence of the urban context on a building's energy performance. Except the quite obvious result, that shading from the surrounding significantly reduces the generated energy, at the same time reduces the cooling load. Buildings with few storeys have more chance to be ZEB in an urban context, such as type T1 and T2. Nevertheless the type of urban context has a big influence on the preferable ZEB type. For types relying mostly on roof mounted systems a uniform height context is better suited, in contrast when a random height context is present the use of facade applied / integrated systems can be of advantage.

6.1 Recommendations for future works

From the results obtained in this work, arise some aspects that seem interesting for a further investigation:

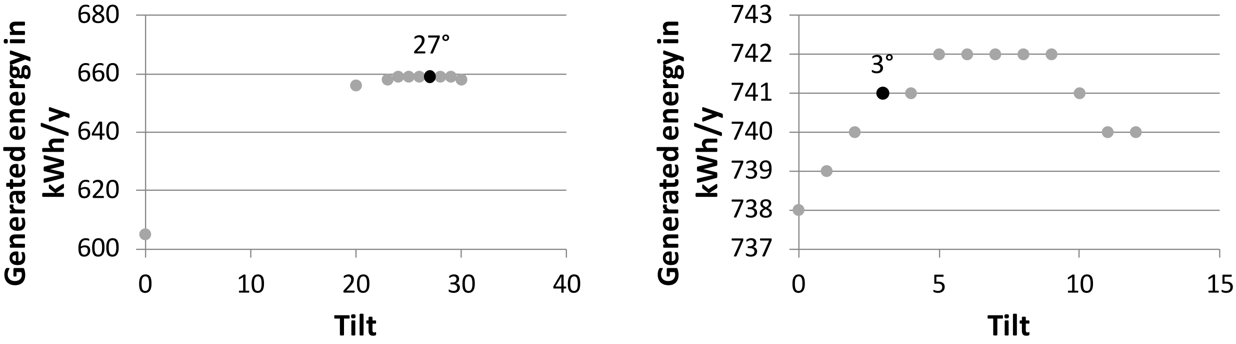
- One main drawback of the PV windows is their generated heat. Further studies for an efficient way of suppressing the heat transfer to the inside should be examined, e.g. ventilated windows, triple glazing windows or different glass types;
- The study was oriented on energetic simulations of the buildings, architectural investigations of the implementation of BIPV technology in the envelope and its aesthetic influence in urban areas should be elicit;
- Only office buildings were simulated, the strategies and concepts should be tested and extended to other building typologies (e.g. multifamily residential buildings, hotels, schools);
- Only two of eight bioclimatic zones in Brazil were evaluated, studies for other zones should be carried out;
- Except PV modules other renewable energy sources can be included into the strategies.

A Appendix

A.1 PV application on the roof

Many references can be found in literature about the calculation of the optimal tilt for the application of PV modules. Different recommendation exist, to avoid losses due to orientation and tilt [44]. In this study, the PV modules on the roof were applied oriented North and inclined with the same angle as the local latitude, 27° in Florianopolis and 3° in Fortaleza. However, the energy yield with other module tilt angles were evaluated to confirm the best tilt for each city.

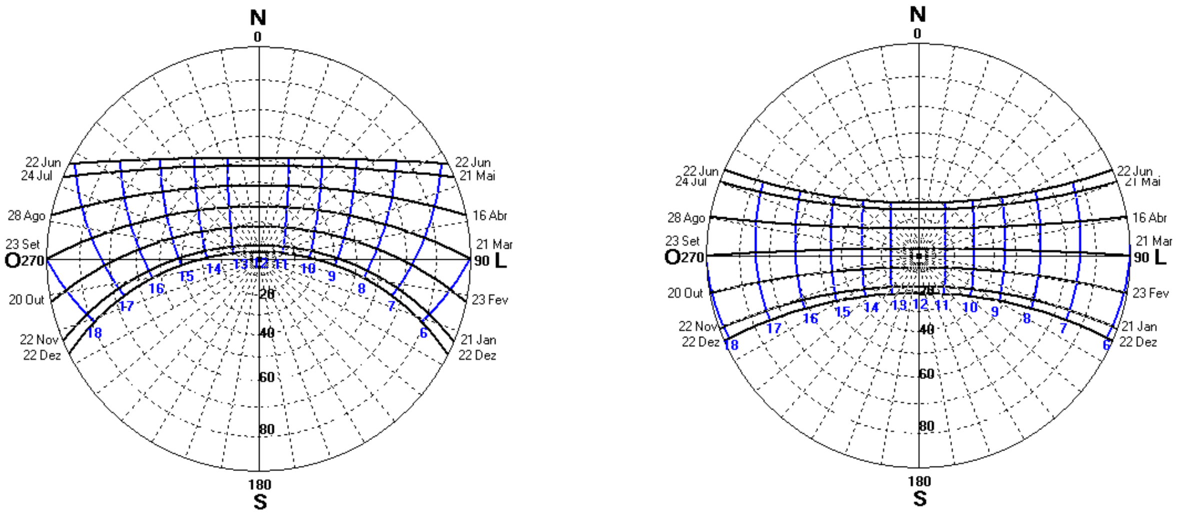
According to the results presented in Figure A.1, in Florianopolis tilt angles between 24° and 29° give almost the same energy generation. For angles below 20° the energy generation slowly decreases. In contrast, in Fortaleza most energy is generated for angles between 5°and 9°. For the latitude angle of 3° a small reduction of 1 kWh/y can be observed.



(a) (b)

Figure A.1: Generated energy for different PV tilt angles for North orientation in Florianopolis (a) and Fortaleza (b).

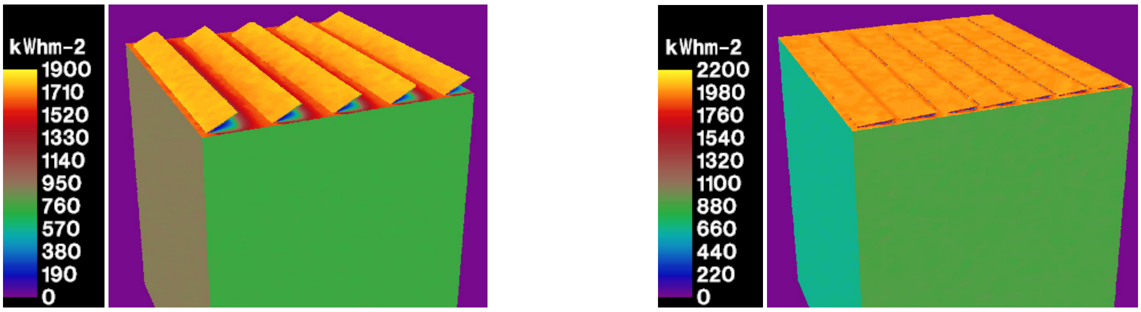
To ensure an optimal energy output and to avoid shading on the PV modules the positioning of the modules and the optimal spacing between them was examined. The space between modules depends on the width of the modules, the tilt angle and the elevation of the sun for which shadowing should be avoided. The elevation of the sun was determined from the sun charts for the both cities. The charts are presented in Figure A.2.



(a) (b)

Figure A.2: Sun charts for Florianopolis (a) and Fortaleza (b) [93].

In Germany the day with the lowest midday sun elevation (12 p.m. on 21st of December) is used to calculate the spacing [181]. As most cities in Brazil are located near the Equator with almost perpendicular sun during the whole year, the day of the lowest elevation and the angle are depending on the city. The sun charts were analyzed for different days and hours, considering solstices and equinoxes (21/03, 22/06, 23/09 and 22/12 at 9 a.m., 12 p.m. and 15 p.m.). In Florianopolis the lowest midday elevation of the sun is 30° on 21st of March and 23rd of September. In Fortaleza the lowest midday elevation is 20° on 22nd of December. The modules spacing was calculated in a way almost no shadowing between 9 a.m. and 5 p.m. occurs on those days. Figure A.3 shows a solar irradiation map with the average of the annual solar irradiation on the modules.



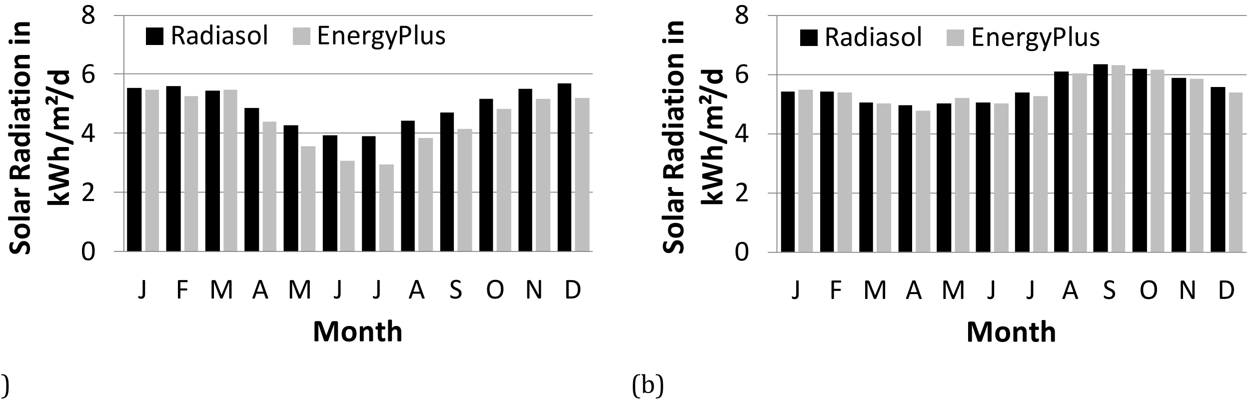
(a) (b)

Figure A.3: Solar irradiation map for Florianopolis (a) and Fortaleza (b).

A.2 Radiasol vs. EnergyPlus: solar irradiation values

A comparison of the solar irradiation on the building calculated with the data from two different programs was made. One of the programs, Radiasol, just gives an average solar irradiation value that can be used for an estimative calculation for the generated energy, e.g for a quick pre-analysis or an initial PV application. With the second one, EnergyPlus, a full thermo-energetic analysis is carried out at the expense of a more complicated modeling process.

The irradiation data obtained from Radiasol and from EnergyPlus were compared in detail to determine the differences between the estimative energy calculation method and the results from the EnergyPlus simulations. Figure A.4 shows the daily solar radiation obtained from Radiasol and EnergyPlus for Florianopolis and Fortaleza. According to the graphics, Radiasol almost always gives higher values than EnergyPlus. For Florianopolis the difference is quite high for the winter months (Jun-Aug). In contrast, for Fortaleza the values are similar for all months.



(a) (b)

Figure A.4: Daily solar irradiation calculated with Radiasol and EnergyPlus in Florianopolis (a) and Fortaleza (b) for the calculation of the generated energy using different methods.

Figure A.5 shows the generated energy calculated with the estimation and the simulation method, and the difference between the both, which is marked as percent values with dots in the figure. The differences are higher for Florianopolis than for Fortaleza, as expected form the irradiation results. The maximum difference is 12 % for the energy generated by the facade installed PVs and 11 % for the totally generated energy. In Fortaleza the totally generated energy differs only 6 % and the energy generated by the PVs installed on the roof has a difference of only 1 %.

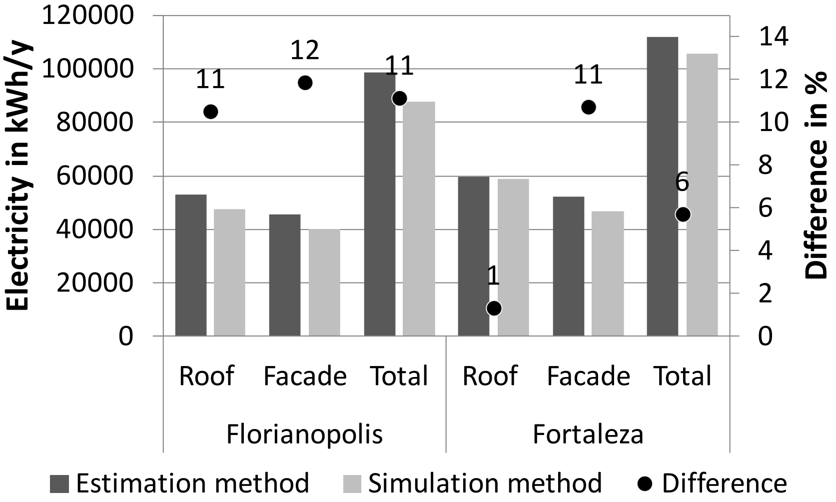
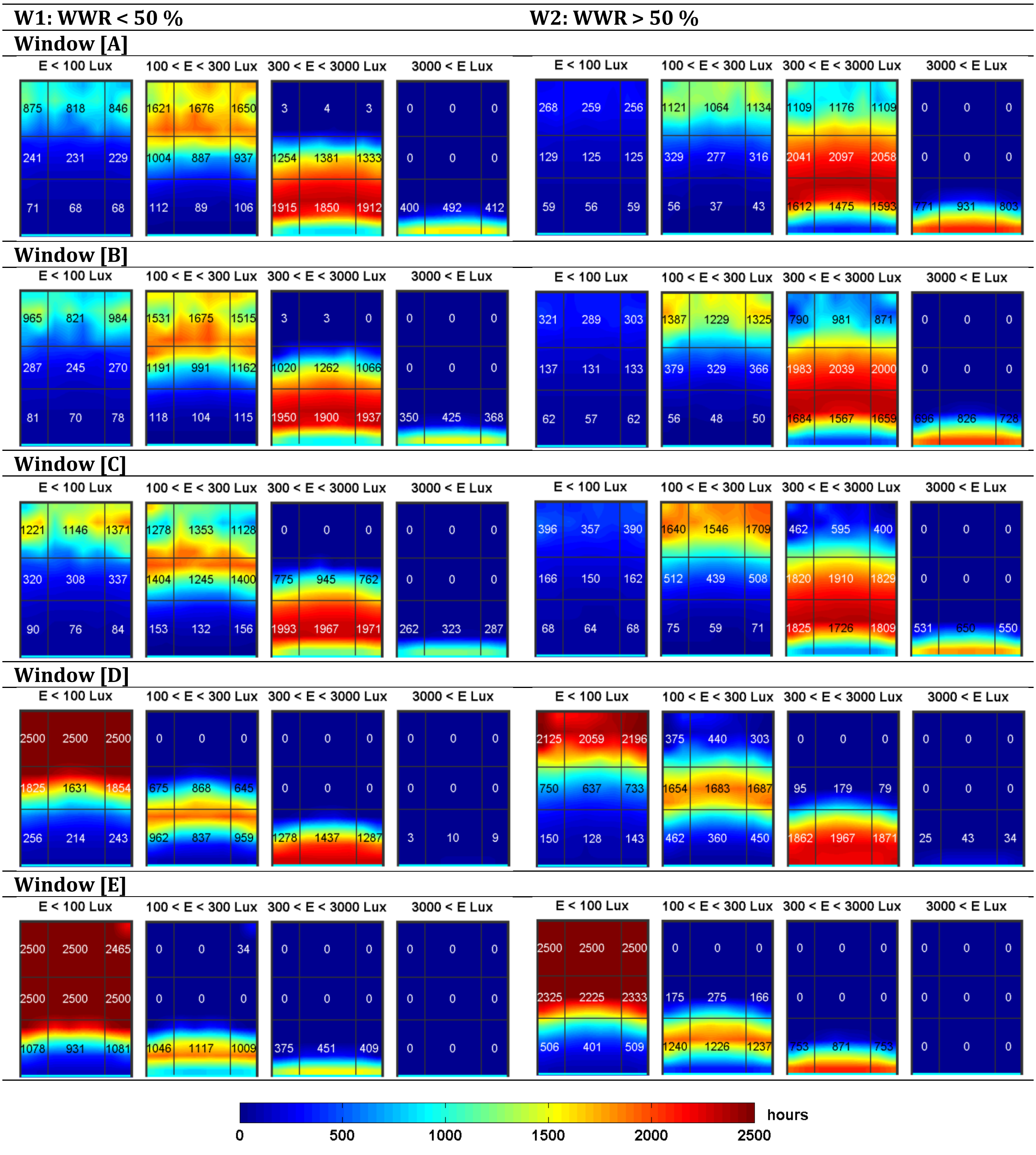


Figure A.5: Difference of the generated energy calculated with estimation and simulation methods for different surfaces in Florianopolis and Fortaleza.

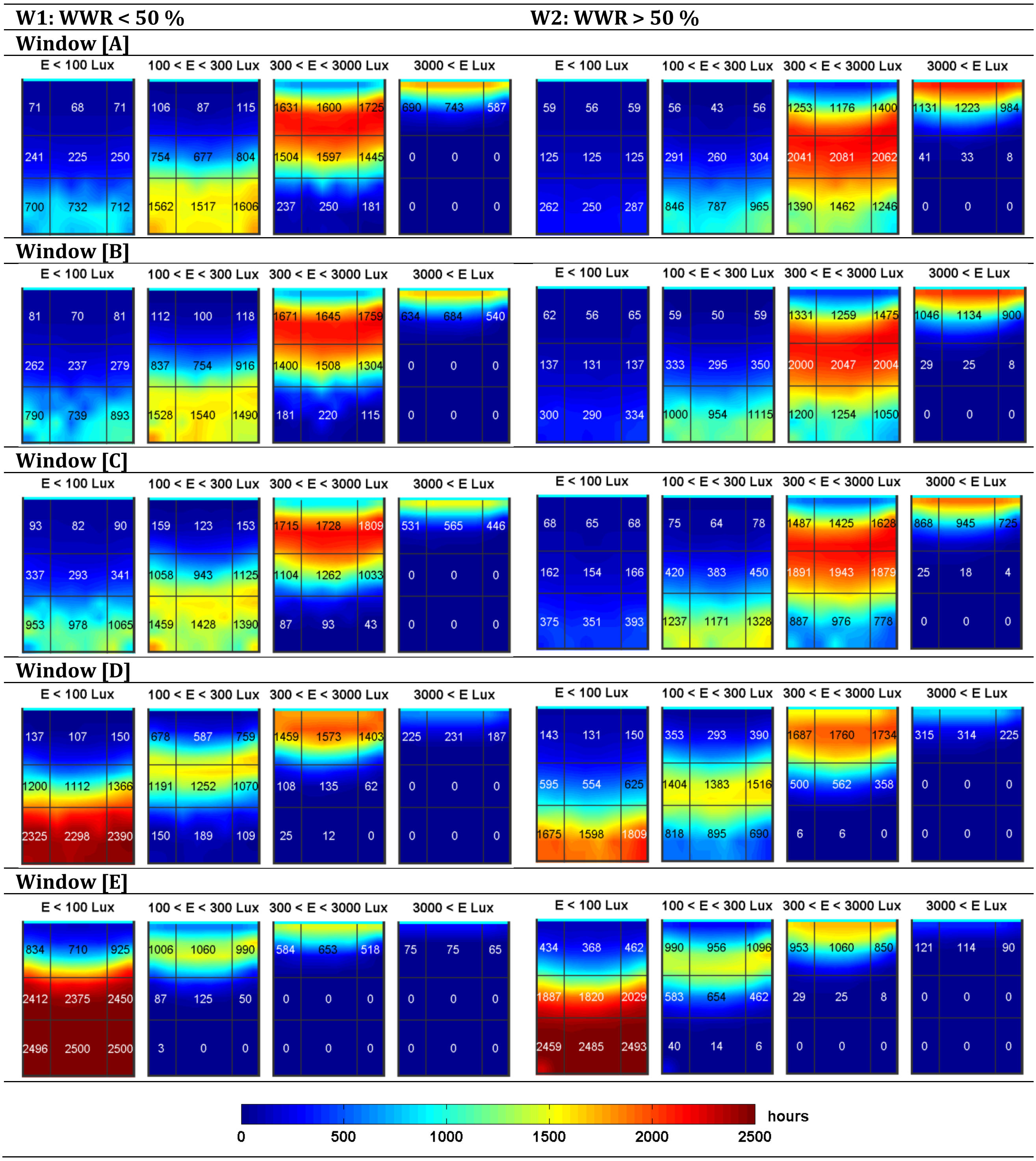
A.3 Useful Daylighting Illuminance (UDI)

South, East and West facade for Florianopolis



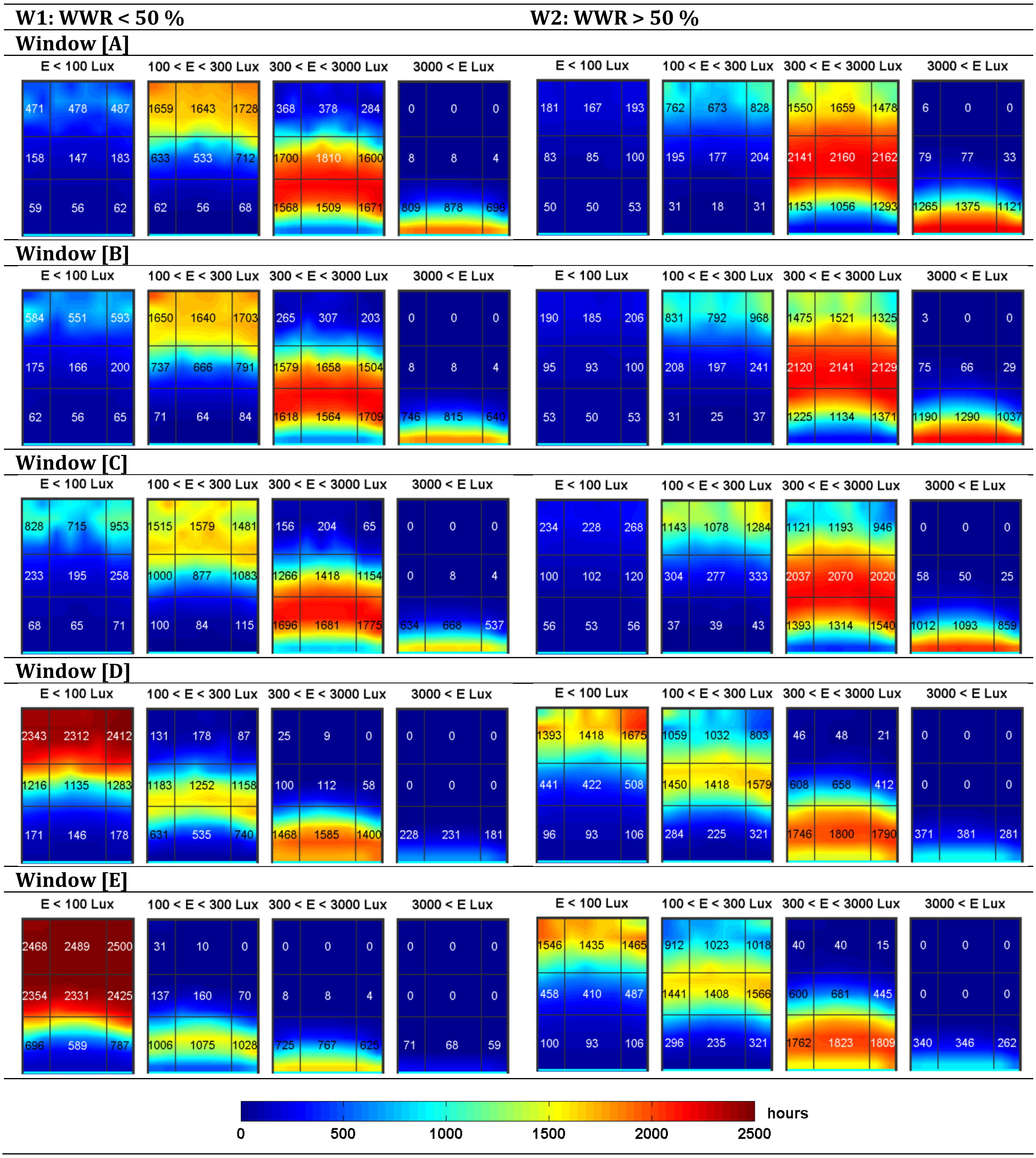
W1: WWR < 50 %				W2: WWR > 50 %			
Window [A]							
E < 100 Lux	100 < E < 300 Lux	300 < E < 3000 Lux	3000 < E Lux	E < 100 Lux	100 < E < 300 Lux	300 < E < 3000 Lux	3000 < E Lux
875 818 846	1621 1676 1650	3 4 3	0 0 0	268 259 256	1121 1064 1134	1109 1176 1109	0 0 0
241 231 229	1004 887 937	1254 1381 1333	0 0 0	129 125 125	329 277 316	2041 2097 2058	0 0 0
71 68 68	112 89 106	1915 1850 1912	400 492 412	59 56 59	56 37 43	1612 1475 1593	771 931 803
Window [B]							
E < 100 Lux	100 < E < 300 Lux	300 < E < 3000 Lux	3000 < E Lux	E < 100 Lux	100 < E < 300 Lux	300 < E < 3000 Lux	3000 < E Lux
965 821 984	1531 1675 1515	3 3 0	0 0 0	321 289 303	1387 1229 1325	790 981 871	0 0 0
287 245 270	1191 991 1162	1020 1262 1066	0 0 0	137 131 133	379 329 366	1983 2039 2000	0 0 0
81 70 78	118 104 115	1950 1900 1937	350 425 368	62 57 62	56 48 50	1684 1567 1659	696 826 728
Window [C]							
E < 100 Lux	100 < E < 300 Lux	300 < E < 3000 Lux	3000 < E Lux	E < 100 Lux	100 < E < 300 Lux	300 < E < 3000 Lux	3000 < E Lux
1221 1146 1371	1278 1353 1128	0 0 0	0 0 0	396 357 390	1640 1546 1709	462 595 400	0 0 0
320 308 337	1404 1245 1400	775 945 762	0 0 0	166 150 162	512 439 508	1820 1910 1829	0 0 0
90 76 84	153 132 156	1993 1967 1971	262 323 287	68 64 68	75 59 71	1825 1726 1809	531 650 550
Window [D]							
E < 100 Lux	100 < E < 300 Lux	300 < E < 3000 Lux	3000 < E Lux	E < 100 Lux	100 < E < 300 Lux	300 < E < 3000 Lux	3000 < E Lux
2500 2500 2500	0 0 0	0 0 0	0 0 0	2125 2059 2196	375 440 303	0 0 0	0 0 0
1825 1631 1854	675 868 645	0 0 0	0 0 0	750 637 733	1654 1683 1687	95 179 79	0 0 0
256 214 243	962 837 959	1278 1437 1287	3 10 9	150 128 143	462 360 450	1862 1967 1871	25 43 34
Window [E]							
E < 100 Lux	100 < E < 300 Lux	300 < E < 3000 Lux	3000 < E Lux	E < 100 Lux	100 < E < 300 Lux	300 < E < 3000 Lux	3000 < E Lux
2500 2500 2465	0 0 34	0 0 0	0 0 0	2500 2500 2500	0 0 0	0 0 0	0 0 0
2500 2500 2500	0 0 0	0 0 0	0 0 0	2325 2225 2333	175 275 166	0 0 0	0 0 0
1078 931 1081	1046 1117 1009	375 451 409	0 0 0	506 401 509	1240 1226 1237	753 871 753	0 0 0

Table A.1: UDI for the South facade in Florianopolis.



W1: WWR < 50 %												W2: WWR > 50 %											
Window [A]																							
E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux			E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux		
71	68	71	106	87	115	1631	1600	1725	690	743	587	59	56	59	56	43	56	1253	1176	1400	1131	1223	984
241	225	250	754	677	804	1504	1597	1445	0	0	0	125	125	125	291	260	304	2041	2081	2062	41	33	8
700	732	712	1562	1517	1606	237	250	181	0	0	0	262	250	287	846	787	965	1390	1462	1246	0	0	0
Window [B]																							
E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux			E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux		
81	70	81	112	100	118	1671	1645	1759	634	684	540	62	56	65	59	50	59	1331	1259	1475	1046	1134	900
262	237	279	837	754	916	1400	1508	1304	0	0	0	137	131	137	333	295	350	2000	2047	2004	29	25	8
790	739	893	1528	1540	1490	181	220	115	0	0	0	300	290	334	1000	954	1115	1200	1254	1050	0	0	0
Window [C]																							
E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux			E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux		
93	82	90	159	123	153	1715	1728	1809	531	565	446	68	65	68	75	64	78	1487	1425	1628	868	945	725
337	293	341	1058	943	1125	1104	1262	1033	0	0	0	162	154	166	420	383	450	1891	1943	1879	25	18	4
953	978	1065	1459	1428	1390	87	93	43	0	0	0	375	351	393	1237	1171	1328	887	976	778	0	0	0
Window [D]																							
E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux			E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux		
137	107	150	678	587	759	1459	1573	1403	225	231	187	143	131	150	353	293	390	1687	1760	1734	315	314	225
1200	1112	1366	1191	1252	1070	108	135	62	0	0	0	595	554	625	1404	1383	1516	500	562	358	0	0	0
2325	2298	2390	150	189	109	25	12	0	0	0	0	1675	1598	1809	818	895	690	6	6	0	0	0	0
Window [E]																							
E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux			E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux		
834	710	925	1006	1060	990	584	653	518	75	75	65	434	368	462	990	956	1096	953	1060	850	121	114	90
2412	2375	2450	87	125	50	0	0	0	0	0	0	1887	1820	2029	583	654	462	29	25	8	0	0	0
2496	2500	2500	3	0	0	0	0	0	0	0	0	2459	2485	2493	40	14	6	0	0	0	0	0	0

Table A.2: UDI for the East facade in Florianopolis.



W1: WWR < 50 % **W2: WWR > 50 %**

Window [A]

E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux			E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux		
471	478	487	1659	1643	1728	368	378	284	0	0	0	181	167	193	762	673	828	1550	1659	1478	6	0	0
158	147	183	633	533	712	1700	1810	1600	8	8	4	83	85	100	195	177	204	2141	2160	2162	79	77	33
59	56	62	62	56	68	1568	1509	1671	809	878	696	50	50	53	31	18	31	1153	1056	1293	1265	1375	1121

Window [B]

E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux			E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux		
584	551	593	1650	1640	1703	265	307	203	0	0	0	190	185	206	831	792	968	1475	1521	1325	3	0	0
175	166	200	737	666	791	1579	1658	1504	8	8	4	95	93	100	208	197	241	2120	2141	2129	75	66	29
62	56	65	71	64	84	1618	1564	1709	746	815	640	53	50	53	31	25	37	1225	1134	1371	1190	1290	1037

Window [C]

E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux			E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux		
828	715	953	1515	1579	1481	156	204	65	0	0	0	234	228	268	1143	1078	1284	1121	1193	946	0	0	0
233	195	258	1000	877	1083	1266	1418	1154	0	8	4	100	102	120	304	277	333	2037	2070	2020	58	50	25
68	65	71	100	84	115	1696	1681	1775	634	668	537	56	53	56	37	39	43	1393	1314	1540	1012	1093	859

Window [D]

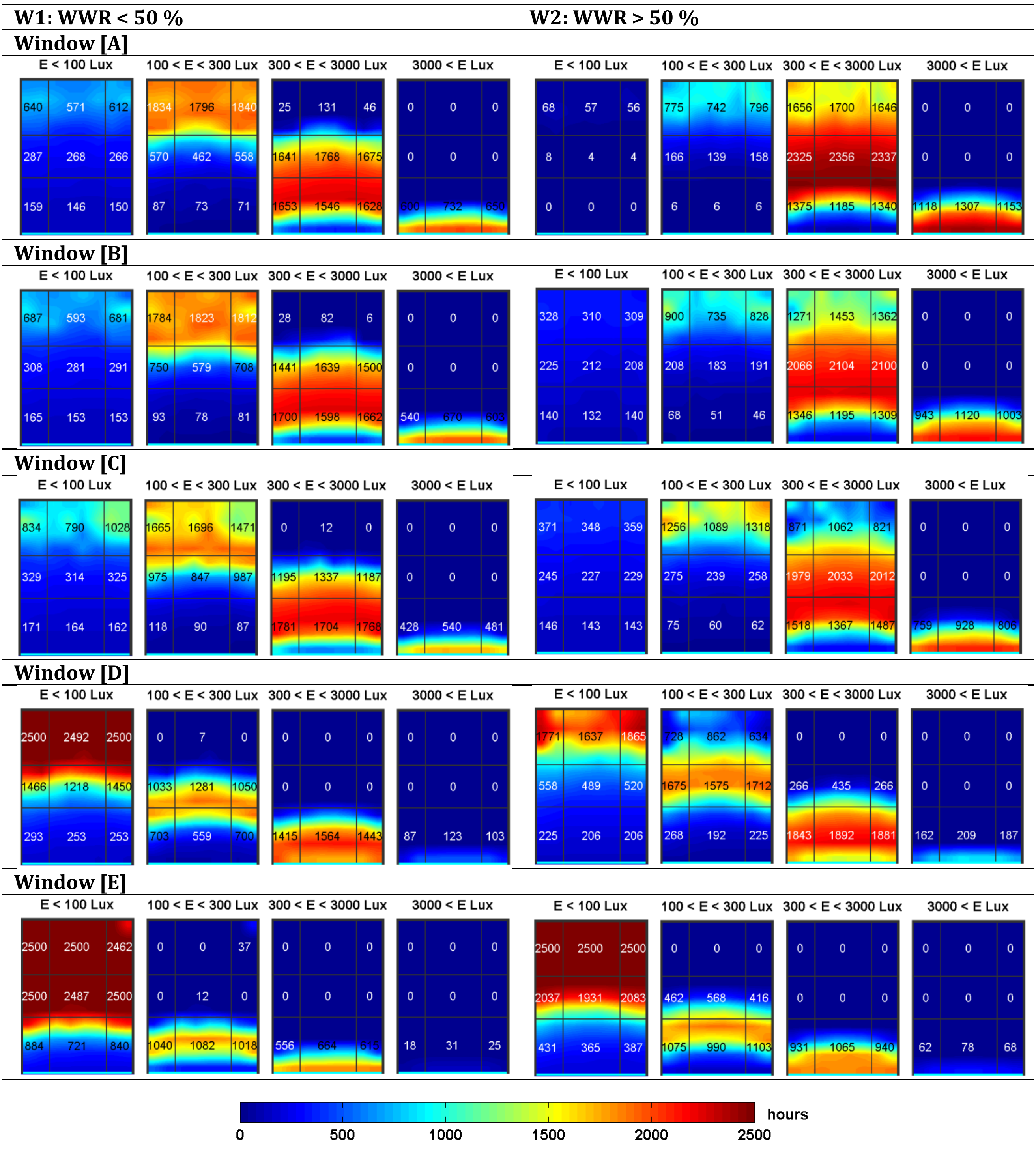
E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux			E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux		
2343	2312	2412	131	178	87	25	9	0	0	0	0	1393	1418	1675	1059	1032	803	46	48	21	0	0	0
1216	1135	1283	1183	1252	1158	100	112	58	0	0	0	441	422	508	1450	1418	1579	608	658	412	0	0	0
171	146	178	631	535	740	1468	1585	1400	228	231	181	96	93	106	284	225	321	1746	1800	1790	371	381	281

Window [E]

E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux			E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux		
2468	2489	2500	31	10	0	0	0	0	0	0	0	1546	1435	1465	912	1023	1018	40	40	15	0	0	0
2354	2331	2425	137	160	70	8	8	4	0	0	0	458	410	487	1441	1408	1566	600	681	445	0	0	0
696	589	787	1006	1075	1028	725	767	625	71	68	59	100	93	106	296	235	321	1762	1823	1809	340	346	262

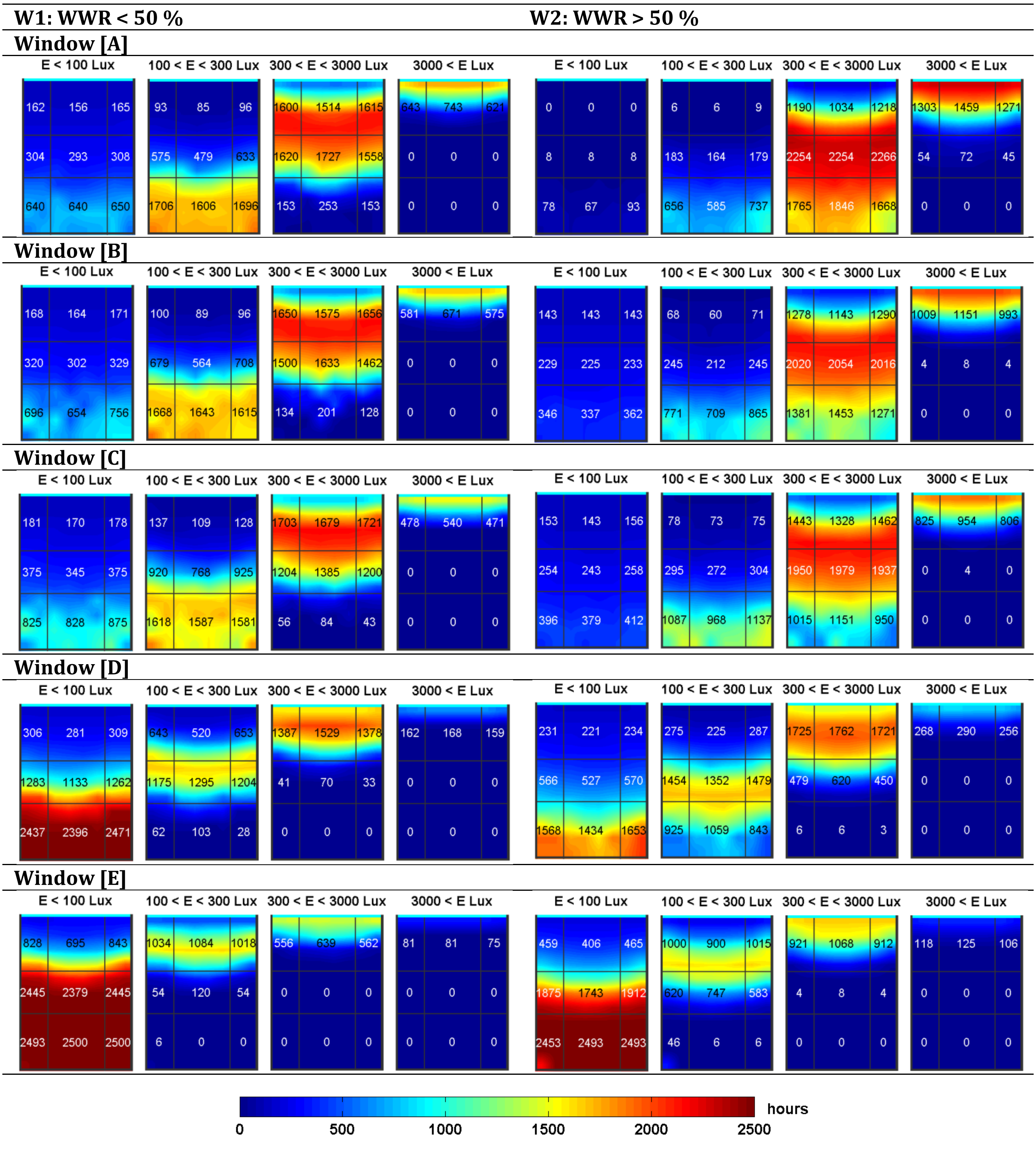
Table A.3: UDI for the West facade in Florianopolis.

South, East and West facade for Fortaleza



	W1: WWR < 50 %				W2: WWR > 50 %			
	E < 100 Lux	100 < E < 300 Lux	300 < E < 3000 Lux	3000 < E Lux	E < 100 Lux	100 < E < 300 Lux	300 < E < 3000 Lux	3000 < E Lux
Window [A]	640 571 612	1834 1796 1840	25 131 46	0 0 0	68 57 56	775 742 796	1656 1700 1646	0 0 0
	287 268 266	570 462 558	1641 1768 1675	0 0 0	8 4 4	166 139 158	2325 2356 2337	0 0 0
	159 146 150	87 73 71	1653 1546 1628	600 732 650	0 0 0	6 6 6	1375 1185 1340	1118 1307 1153
Window [B]	687 593 681	1784 1823 1812	28 82 6	0 0 0	328 310 309	900 735 828	1271 1453 1362	0 0 0
	308 281 291	750 579 708	1441 1639 1500	0 0 0	225 212 208	208 183 191	2066 2104 2100	0 0 0
	165 153 153	93 78 81	1700 1598 1662	540 670 603	140 132 140	68 51 46	1346 1195 1309	943 1120 1003
Window [C]	834 790 1028	1665 1696 1471	0 12 0	0 0 0	371 348 359	1256 1089 1318	871 1062 821	0 0 0
	329 314 325	975 847 987	1195 1337 1187	0 0 0	245 227 229	275 239 258	1979 2033 2012	0 0 0
	171 164 162	118 90 87	1781 1704 1768	428 540 481	146 143 143	75 60 62	1518 1367 1487	759 928 806
Window [D]	2500 2492 2500	0 7 0	0 0 0	0 0 0	1771 1637 1865	728 862 634	0 0 0	0 0 0
	1466 1218 1450	1033 1281 1050	0 0 0	0 0 0	558 489 520	1675 1575 1712	266 435 266	0 0 0
	293 253 253	703 559 700	1415 1564 1443	87 123 103	225 206 206	268 192 225	1843 1892 1881	162 209 187
Window [E]	2500 2500 2462	0 0 37	0 0 0	0 0 0	2500 2500 2500	0 0 0	0 0 0	0 0 0
	2500 2487 2500	0 12 0	0 0 0	0 0 0	2037 1931 2083	462 568 416	0 0 0	0 0 0
	884 721 840	1040 1082 1018	556 664 615	18 31 25	431 365 387	1075 990 1103	931 1065 940	62 78 68

Table A.4: UDI for the South facade in Fortaleza.



W1: WWR < 50 %　**W2: WWR > 50 %**

Window [A]

W1: WWR < 50 %

E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux		
162	156	165	93	85	96	1600	1514	1615	643	743	621
304	293	308	575	479	633	1620	1727	1558	0	0	0
640	640	650	1706	1606	1696	153	253	153	0	0	0

W2: WWR > 50 %

E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux		
0	0	0	6	6	9	1190	1034	1218	1303	1459	1271
8	8	8	183	164	179	2254	2254	2266	54	72	45
78	67	93	656	585	737	1765	1846	1668	0	0	0

Window [B]

W1: WWR < 50 %

E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux		
168	164	171	100	89	96	1650	1575	1656	581	671	575
320	302	329	679	564	708	1500	1633	1462	0	0	0
696	654	756	1668	1643	1615	134	201	128	0	0	0

W2: WWR > 50 %

E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux		
143	143	143	68	60	71	1278	1143	1290	1009	1151	993
229	225	233	245	212	245	2020	2054	2016	4	8	4
346	337	362	771	709	865	1381	1453	1271	0	0	0

Window [C]

W1: WWR < 50 %

E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux		
181	170	178	137	109	128	1703	1679	1721	478	540	471
375	345	375	920	768	925	1204	1385	1200	0	0	0
825	828	875	1618	1587	1581	56	84	43	0	0	0

W2: WWR > 50 %

E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux		
153	143	156	78	73	75	1443	1328	1462	825	954	806
254	243	258	295	272	304	1950	1979	1937	0	4	0
396	379	412	1087	968	1137	1015	1151	950	0	0	0

Window [D]

W1: WWR < 50 %

E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux		
306	281	309	643	520	653	1387	1529	1378	162	168	159
1283	1133	1262	1175	1295	1204	41	70	33	0	0	0
2437	2396	2471	62	103	28	0	0	0	0	0	0

W2: WWR > 50 %

E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux		
231	221	234	275	225	287	1725	1762	1721	268	290	256
566	527	570	1454	1352	1479	479	620	450	0	0	0
1568	1434	1653	925	1059	843	6	6	3	0	0	0

Window [E]

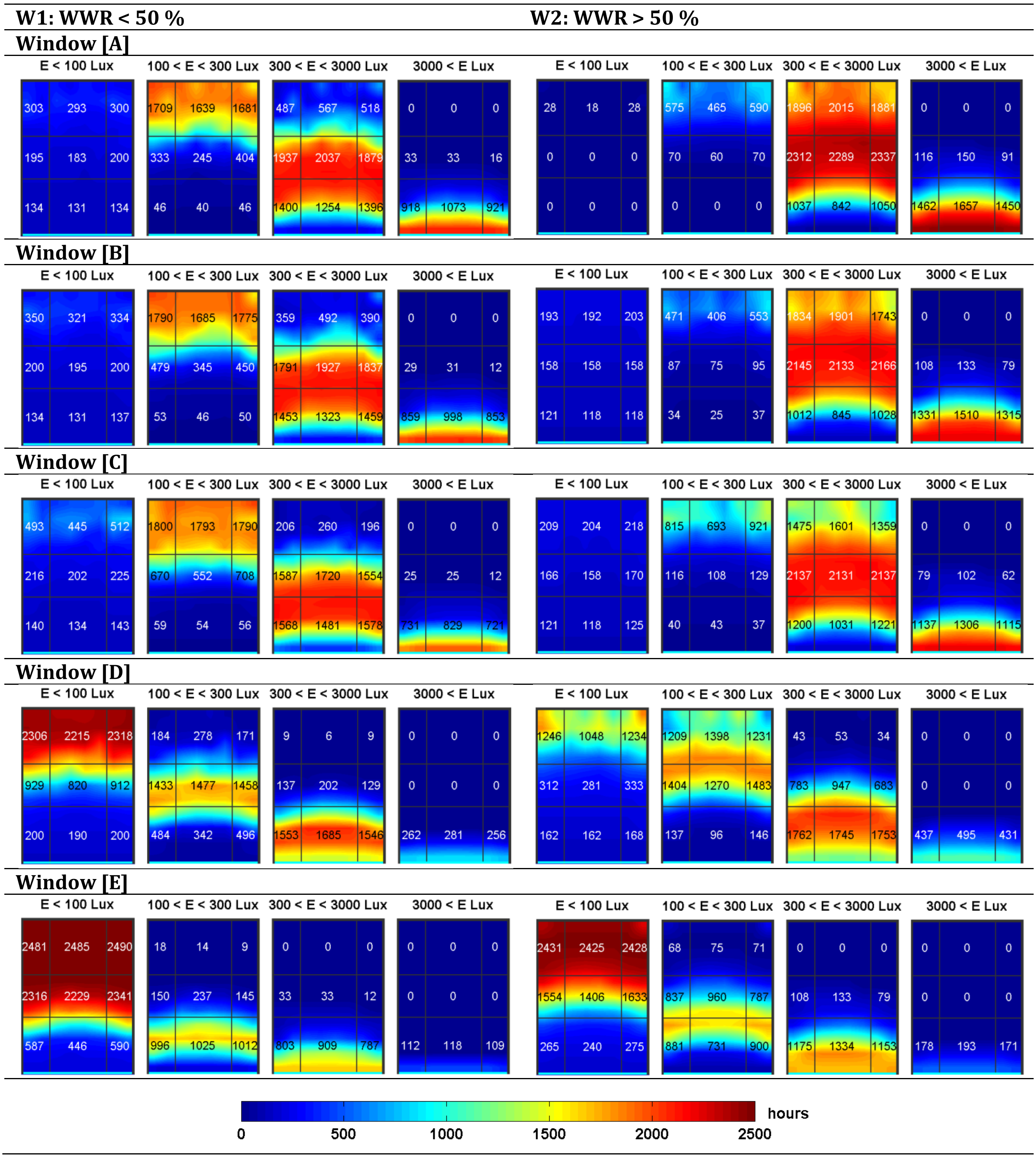
W1: WWR < 50 %

E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux		
828	695	843	1034	1084	1018	556	639	562	81	81	75
2445	2379	2445	54	120	54	0	0	0	0	0	0
2493	2500	2500	6	0	0	0	0	0	0	0	0

W2: WWR > 50 %

E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux		
459	406	465	1000	900	1015	921	1068	912	118	125	106
1875	1743	1912	620	747	583	4	8	4	0	0	0
2453	2493	2493	46	6	6	0	0	0	0	0	0

Table A.5: UDI for the East facade in Fortaleza.



Window [A]

W1: WWR < 50 %												W2: WWR > 50 %											
E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux			E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux		
303	293	300	1709	1639	1681	487	567	518	0	0	0	28	18	28	575	465	590	1896	2015	1881	0	0	0
195	183	200	333	245	404	1937	2037	1879	33	33	16	0	0	0	70	60	70	2312	2289	2337	116	150	91
134	131	134	46	40	46	1400	1254	1396	918	1073	921	0	0	0	0	0	0	1037	842	1050	1462	1657	1450

Window [B]

W1: WWR < 50 %												W2: WWR > 50 %											
E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux			E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux		
350	321	334	1790	1685	1775	359	492	390	0	0	0	193	192	203	471	406	553	1834	1901	1743	0	0	0
200	195	200	479	345	450	1791	1927	1837	29	31	12	158	158	158	87	75	95	2145	2133	2166	108	133	79
134	131	137	53	46	50	1453	1323	1459	859	998	853	121	118	118	34	25	37	1012	845	1028	1331	1510	1315

Window [C]

W1: WWR < 50 %												W2: WWR > 50 %											
E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux			E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux		
493	445	512	1800	1793	1790	206	260	196	0	0	0	209	204	218	815	693	921	1475	1601	1359	0	0	0
216	202	225	670	552	708	1587	1720	1554	25	25	12	166	158	170	116	108	129	2137	2131	2137	79	102	62
140	134	143	59	54	56	1568	1481	1578	731	829	721	121	118	125	40	43	37	1200	1031	1221	1137	1306	1115

Window [D]

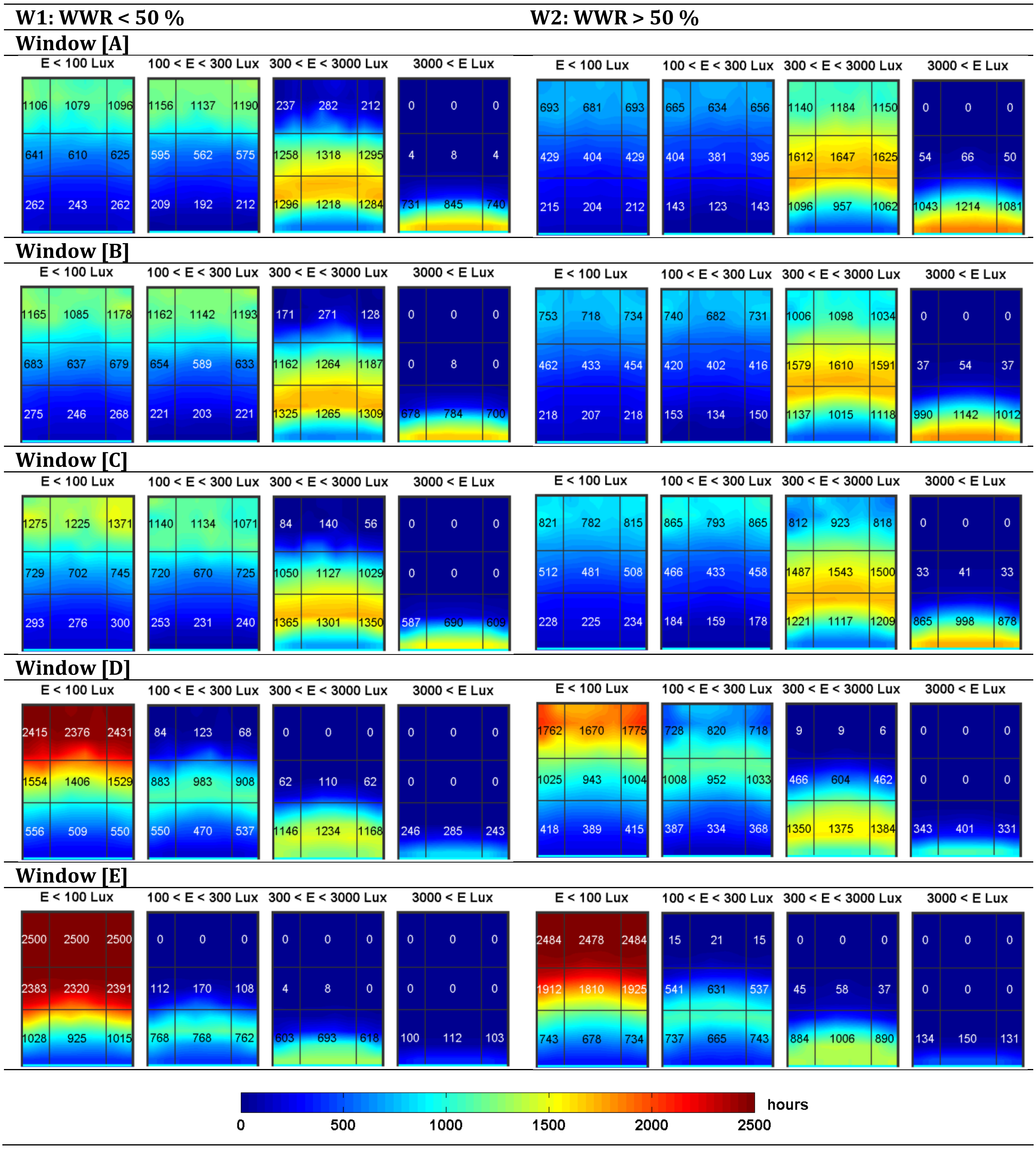
W1: WWR < 50 %												W2: WWR > 50 %											
E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux			E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux		
2306	2215	2318	184	278	171	9	6	9	0	0	0	1246	1048	1234	1209	1398	1231	43	53	34	0	0	0
929	820	912	1433	1477	1458	137	202	129	0	0	0	312	281	333	1404	1270	1483	783	947	683	0	0	0
200	190	200	484	342	496	1553	1685	1546	262	281	256	162	162	168	137	96	146	1762	1745	1753	437	495	431

Window [E]

W1: WWR < 50 %												W2: WWR > 50 %											
E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux			E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux		
2481	2485	2490	18	14	9	0	0	0	0	0	0	2431	2425	2428	68	75	71	0	0	0	0	0	0
2316	2229	2341	150	237	145	33	33	12	0	0	0	1554	1406	1633	837	960	787	108	133	79	0	0	0
587	446	590	996	1025	1012	803	909	787	112	118	109	265	240	275	881	731	900	1175	1334	1153	178	193	171

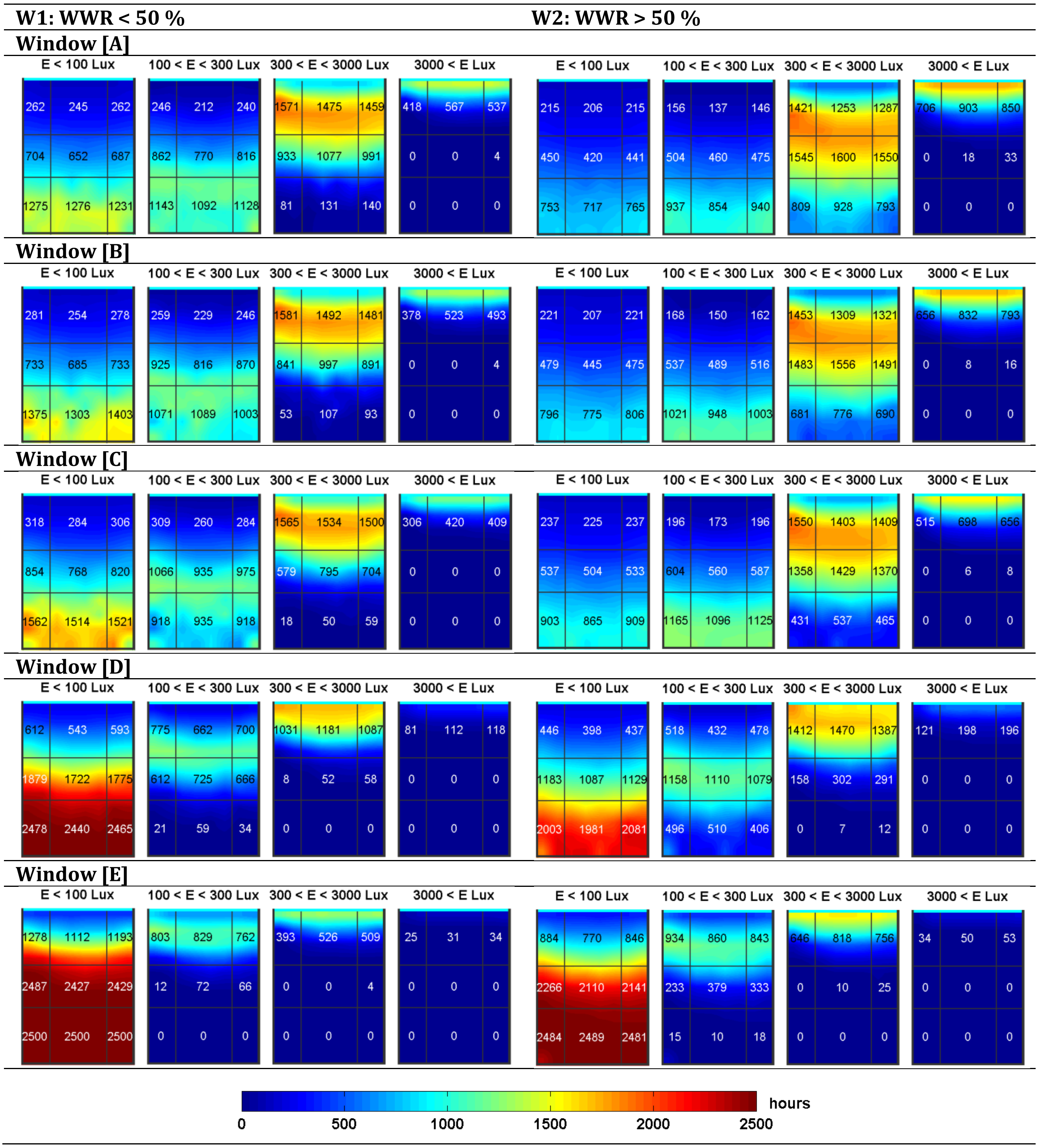
Table A.6: UDI for the West facade in Fortaleza.

South, East and West facade for Frankfurt



	W1: WWR < 50 %				W2: WWR > 50 %			
	E < 100 Lux	100 < E < 300 Lux	300 < E < 3000 Lux	3000 < E Lux	E < 100 Lux	100 < E < 300 Lux	300 < E < 3000 Lux	3000 < E Lux
Window [A]	1106 1079 1096	1156 1137 1190	237 282 212	0 0 0	693 681 693	665 634 656	1140 1184 1150	0 0 0
	641 610 625	595 562 575	1258 1318 1295	4 8 4	429 404 429	404 381 395	1612 1647 1625	54 66 50
	262 243 262	209 192 212	1296 1218 1284	731 845 740	215 204 212	143 123 143	1096 957 1062	1043 1214 1081
Window [B]	1165 1085 1178	1162 1142 1193	171 271 128	0 0 0	753 718 734	740 682 731	1006 1098 1034	0 0 0
	683 637 679	654 589 633	1162 1264 1187	0 8 0	462 433 454	420 402 416	1579 1610 1591	37 54 37
	275 246 268	221 203 221	1325 1265 1309	678 784 700	218 207 218	153 134 150	1137 1015 1118	990 1142 1012
Window [C]	1275 1225 1371	1140 1134 1071	84 140 56	0 0 0	821 782 815	865 793 865	812 923 818	0 0 0
	729 702 745	720 670 725	1050 1127 1029	0 0 0	512 481 508	466 433 458	1487 1543 1500	33 41 33
	293 276 300	253 231 240	1365 1301 1350	587 690 609	228 225 234	184 159 178	1221 1117 1209	865 998 878
Window [D]	2415 2376 2431	84 123 68	0 0 0	0 0 0	1762 1670 1775	728 820 718	9 9 6	0 0 0
	1554 1406 1529	883 983 908	62 110 62	0 0 0	1025 943 1004	1008 952 1033	466 604 462	0 0 0
	556 509 550	550 470 537	1146 1234 1168	246 285 243	418 389 415	387 334 368	1350 1375 1384	343 401 331
Window [E]	2500 2500 2500	0 0 0	0 0 0	0 0 0	2484 2478 2484	15 21 15	0 0 0	0 0 0
	2383 2320 2391	112 170 108	4 8 0	0 0 0	1912 1810 1925	541 631 537	45 58 37	0 0 0
	1028 925 1015	768 768 762	603 693 618	100 112 103	743 678 734	737 665 743	884 1006 890	134 150 131

Table A.7: UDI for the South facade in Frankfurt.



W1: WWR < 50 %

Window [A]

E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux		
262	245	262	246	212	240	1571	1475	1459	418	567	537
704	652	687	862	770	816	933	1077	991	0	0	4
1275	1276	1231	1143	1092	1128	81	131	140	0	0	0

Window [B]

E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux		
281	254	278	259	229	246	1581	1492	1481	378	523	493
733	685	733	925	816	870	841	997	891	0	0	4
1375	1303	1403	1071	1089	1003	53	107	93	0	0	0

Window [C]

E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux		
318	284	306	309	260	284	1565	1534	1500	306	420	409
854	768	820	1066	935	975	579	795	704	0	0	0
1562	1514	1521	918	935	918	18	50	59	0	0	0

Window [D]

E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux		
612	543	593	775	662	700	1031	1181	1087	81	112	118
1879	1722	1775	612	725	666	8	52	58	0	0	0
2478	2440	2465	21	59	34	0	0	0	0	0	0

Window [E]

E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux		
1278	1112	1193	803	829	762	393	526	509	25	31	34
2487	2427	2429	12	72	66	0	0	4	0	0	0
2500	2500	2500	0	0	0	0	0	0	0	0	0

W2: WWR > 50 %

Window [A]

E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux		
215	206	215	156	137	146	1421	1253	1287	706	903	850
450	420	441	504	460	475	1545	1600	1550	0	18	33
753	717	765	937	854	940	809	928	793	0	0	0

Window [B]

E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux		
221	207	221	168	150	162	1453	1309	1321	656	832	793
479	445	475	537	489	516	1483	1556	1491	0	8	16
796	775	806	1021	948	1003	681	776	690	0	0	0

Window [C]

E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux		
237	225	237	196	173	196	1550	1403	1409	515	698	656
537	504	533	604	560	587	1358	1429	1370	0	6	8
903	865	909	1165	1096	1125	431	537	465	0	0	0

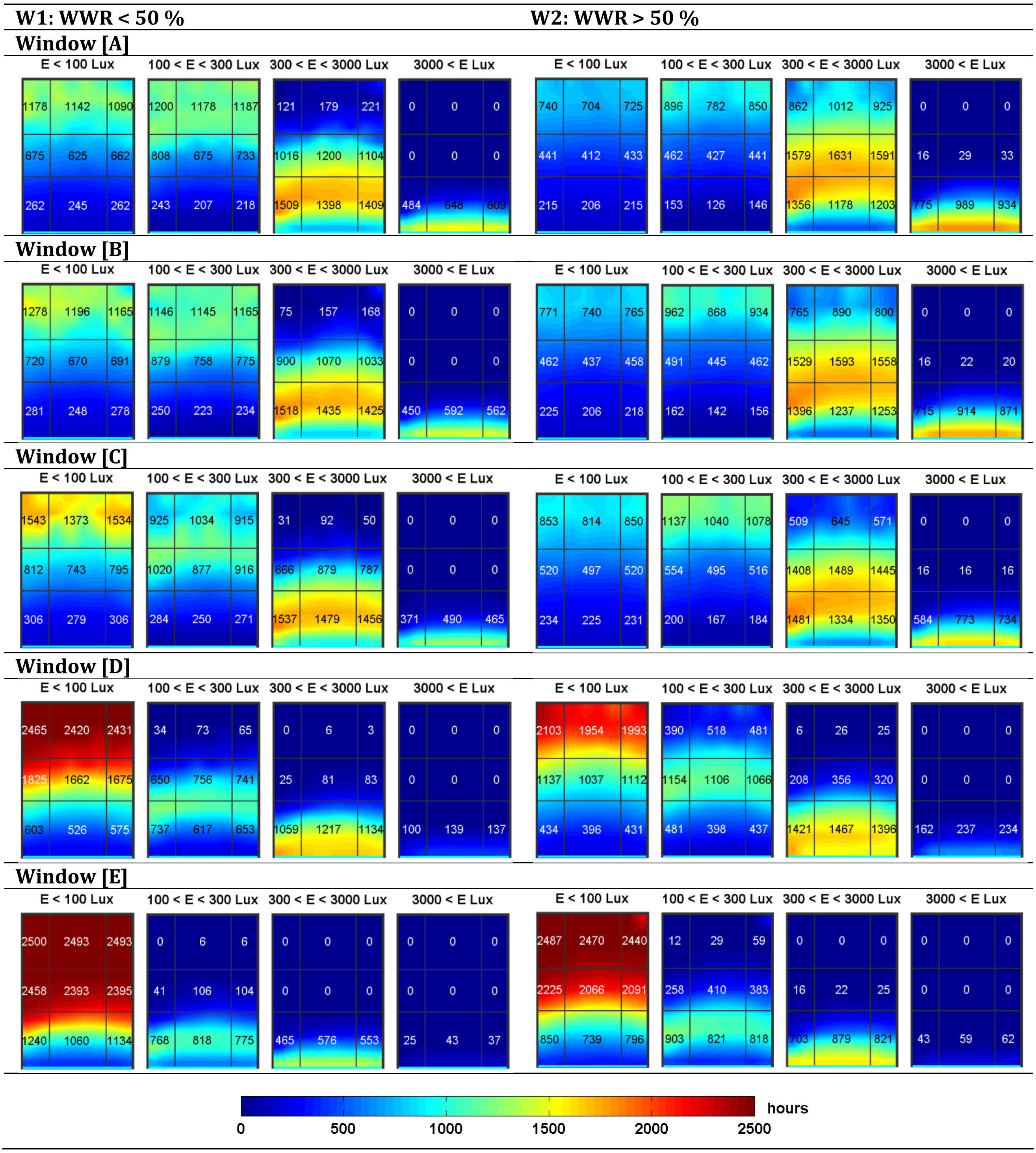
Window [D]

E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux		
446	398	437	518	432	478	1412	1470	1387	121	198	196
1183	1087	1129	1158	1110	1079	158	302	291	0	0	0
2003	1981	2081	496	510	406	0	7	12	0	0	0

Window [E]

E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux		
884	770	846	934	860	843	646	818	756	34	50	53
2266	2110	2141	233	379	333	0	10	25	0	0	0
2484	2489	2481	15	10	18	0	0	0	0	0	0

Table A.8: UDI for the East facade in Frankfurt.



Window [A]

W1: WWR < 50 %												W2: WWR > 50 %											
E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux			E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux		
1178	1142	1090	1200	1178	1187	121	179	221	0	0	0	740	704	725	896	782	850	862	1012	925	0	0	0
675	625	662	808	675	733	1016	1200	1104	0	0	0	441	412	433	462	427	441	1579	1631	1591	16	29	33
262	245	262	243	207	218	1509	1398	1409	484	648	609	215	206	215	153	126	146	1356	1178	1203	775	989	934

Window [B]

W1: WWR < 50 %												W2: WWR > 50 %											
E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux			E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux		
1278	1196	1165	1146	1145	1165	75	157	168	0	0	0	771	740	765	962	868	934	765	890	800	0	0	0
720	670	691	879	758	775	900	1070	1033	0	0	0	462	437	458	491	445	462	1529	1593	1558	16	22	20
281	248	278	250	223	234	1518	1435	1425	450	592	562	225	206	218	162	142	156	1396	1237	1253	715	914	871

Window [C]

W1: WWR < 50 %												W2: WWR > 50 %											
E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux			E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux		
1543	1373	1534	925	1034	915	31	92	50	0	0	0	853	814	850	1137	1040	1078	509	645	571	0	0	0
812	743	795	1020	877	916	666	879	787	0	0	0	520	497	520	554	495	516	1408	1489	1445	16	16	16
306	279	306	284	250	271	1537	1479	1456	371	490	465	234	225	231	200	167	184	1481	1334	1350	584	773	734

Window [D]

W1: WWR < 50 %												W2: WWR > 50 %											
E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux			E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux		
2465	2420	2431	34	73	65	0	6	3	0	0	0	2103	1954	1993	390	518	481	6	26	25	0	0	0
1825	1662	1675	650	756	741	25	81	83	0	0	0	1137	1037	1112	1154	1106	1066	208	356	320	0	0	0
603	526	575	737	617	653	1059	1217	1134	100	139	137	434	396	431	481	398	437	1421	1467	1396	162	237	234

Window [E]

W1: WWR < 50 %												W2: WWR > 50 %											
E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux			E < 100 Lux			100 < E < 300 Lux			300 < E < 3000 Lux			3000 < E Lux		
2500	2493	2493	0	6	6	0	0	0	0	0	0	2487	2470	2440	12	29	59	0	0	0	0	0	0
2458	2393	2395	41	106	104	0	0	0	0	0	0	2225	2066	2091	258	410	383	16	22	25	0	0	0
1240	1060	1134	768	818	775	465	576	553	25	43	37	850	739	796	903	821	818	703	879	821	43	59	62

Table A.9: UDI for the West facade in Frankfurt.

A.4 A shading device study for office building windows

A study to determine the ideal solar protection was carried out. Four different systems were selected for the analysis and a room without solar protection was used for comparison (Table A.10). The mobile venetian blinds models (M3, M4 and M5), were evaluated using the venetian blind inside and outside of the window.

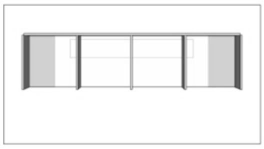
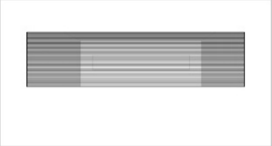
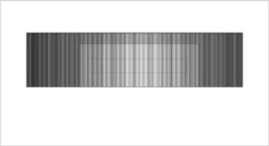
Model		Shading device	Configuration
M1		No shading	
M2		Overhangs and fins	Overhang: 4 m x 0.5 m Fins: 1 m x 0.5 m Separation: 0.5 m Reflectance: 50 %
M3		Venetian blind (horizontal 90°) a = inside b = outside	Width: 0.025 m Slat separation: 0.018 m Reflectance: 80 %
M4		Venetian blind (vertical 90°) a = inside b = outside	Width: 0.025 m Slat separation: 0.018 m Reflectance: 80 %
M5		Venetian blind (horizontal 45°) a = inside b = outside	Width: 0.025 m Slat separation: 0.018 m Reflectance: 80 %

Table A.10: Models with different solar protection systems.

The simulations were carried out using Daysim and EnergyPlus as described in chapter 3. In addition, to evaluate mobile venetian blinds the dynamic shading device mode was activated in Daysim (Advanced), which considers opening and closing of the blinds during the simulation. In EnergyPlus a shading control object was selected to reduce the zone's cooling demands. The object 'OnIfHighSolarOnWindow' was used with a setpoint of 50 W/m^2, as recommended in EnergyPlus manual [58]. That means, the venetian blinds are deployed when the solar radiation incident on the window exceeds 50 W/m^2.

The results below were obtained for the office room in Fortaleza (South facade). It helped to improve the strategy for the development of the optimal office building models used in this thesis. Figure A.6 shows the results of the simulations. The use of mobile horizontal venetian blinds with a tilt of 90° inside the room provided the highest reduction of the annual energy consumption (2 %) of the three different systems

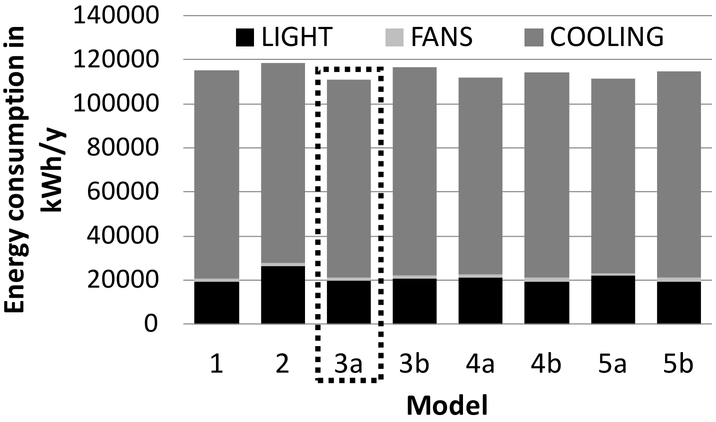


Figure A.6: Annual energy consumption with different solar protection systems in Fortaleza.

Figure A.7 presents the final configuration of the solar protection for the South oriented office room, in Fortaleza. The overhang was used together with the horizontal mobile venetian blind to optimally reduce the energy consumption for cooling, since for regions near the Equator not only the direct solar radiation should be avoided, but also radiative heat gains.

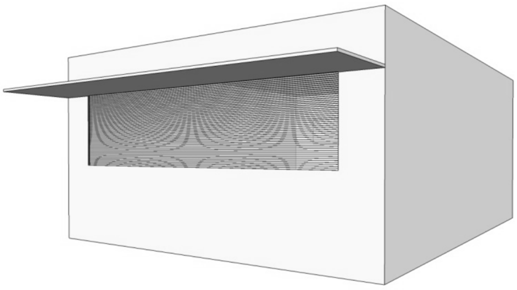
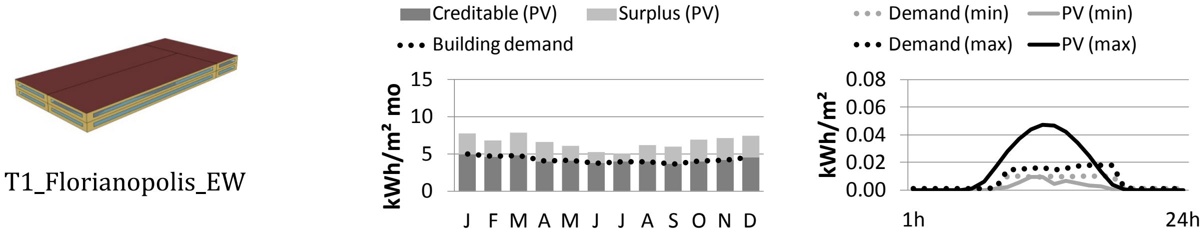


Figure A.7: Final configuration of solar protection system in Fortaleza oriented to South.

A.5 Load match and grid interaction results

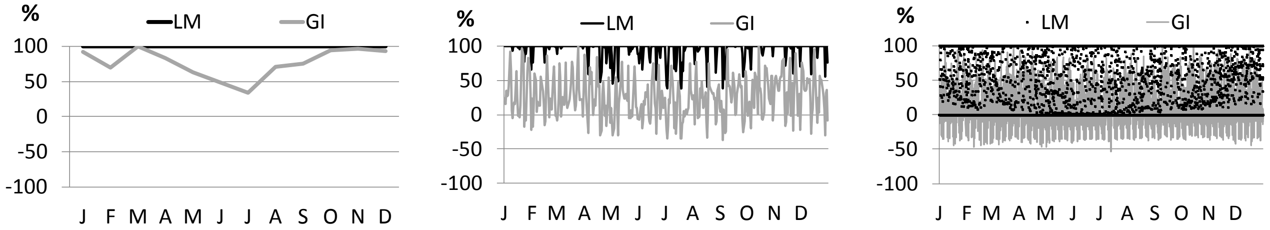
This subsection presents the results from the T1 to T8 types for East-West orientation in Florianopolis and North-South and East-West orientations in Fortaleza.

East-West orientation for Florianopolis



(a) (b) (c)

Figure A.8: Building demand and generated energy for T1 (a) in monthly (b) and daily (c) profiles for East-West facade in Florianopolis.



(d) (e) (f)

Figure A.9: Load match (LM) and grid interaction (GI) for T1 in monthly (d), daily (e) and hourly (f) profiles for East-West facade in Florianopolis.

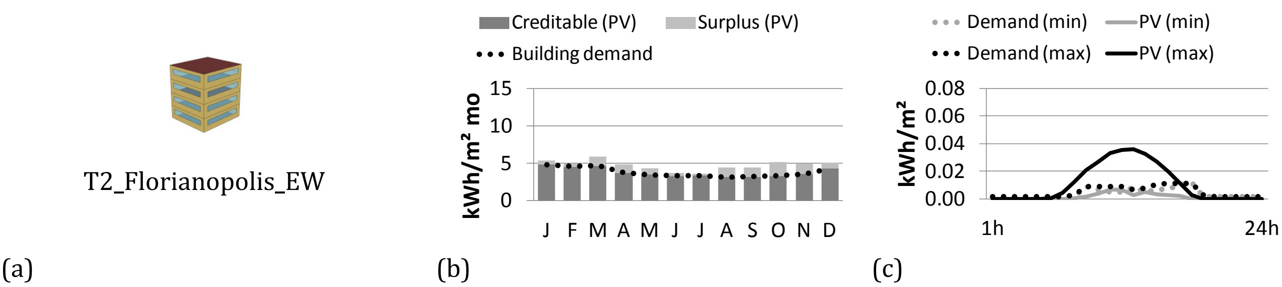


Figure A.10: Building demand and generated energy for T2 (a) in monthly (b) and daily (c) profiles for East-West facade in Florianopolis.

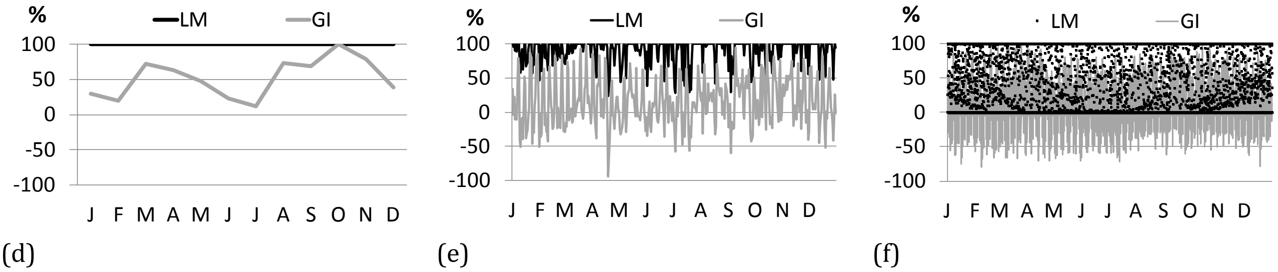


Figure A.11: Load match (LM) and grid interaction (GI) for T2 in monthly (d), daily (e) and hourly (f) profiles for East-West facade in Florianopolis.

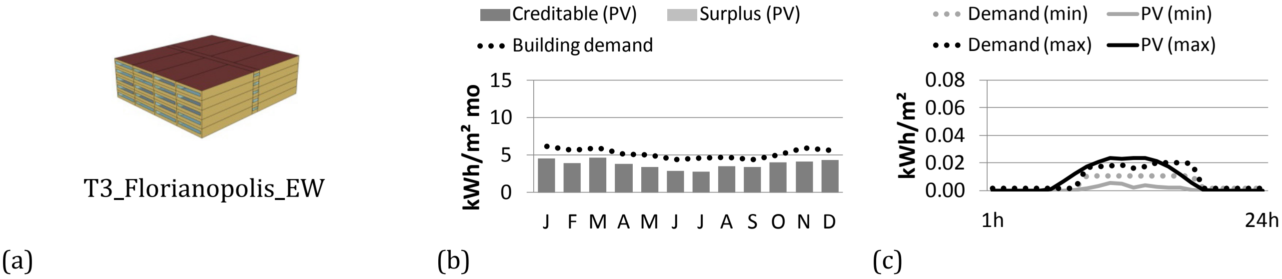


Figure A.12: Building demand and generated energy for T3 (a) in monthly (b) and daily (c) profiles for East-West facade in Florianopolis.

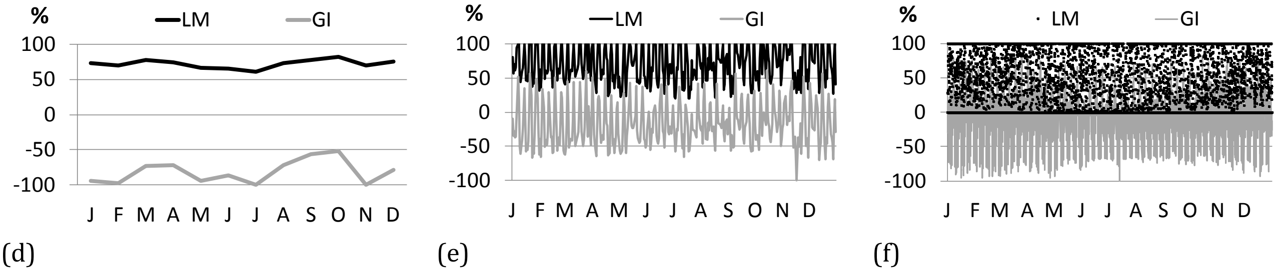
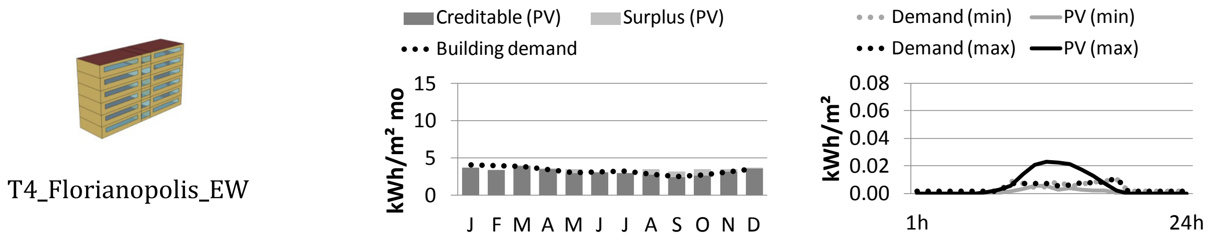
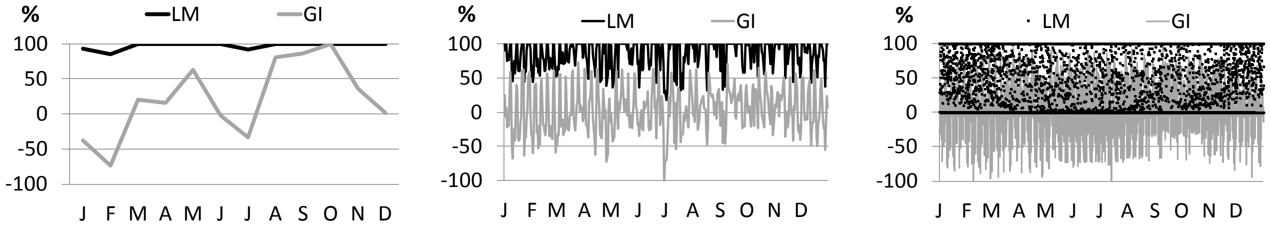


Figure A.13: Load match (LM) and grid interaction (GI) for T3 in monthly (d), daily (e) and hourly (f) profiles for East-West facade in Florianopolis.



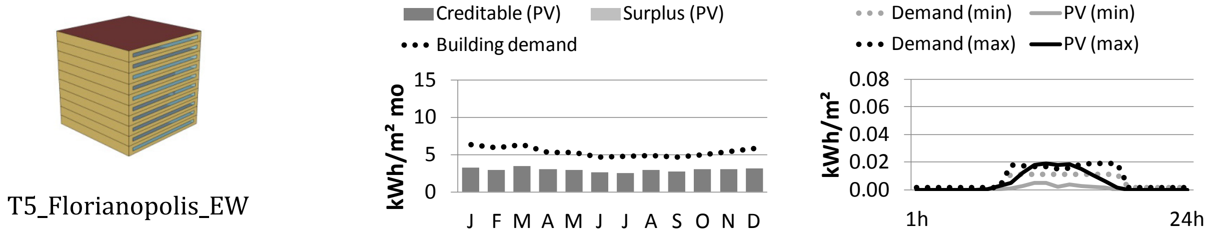
(a) (b) (c)

Figure A.14: Building demand and generated energy for T4 (a) in monthly (b) and daily (c) profiles for East-West facade in Florianopolis.



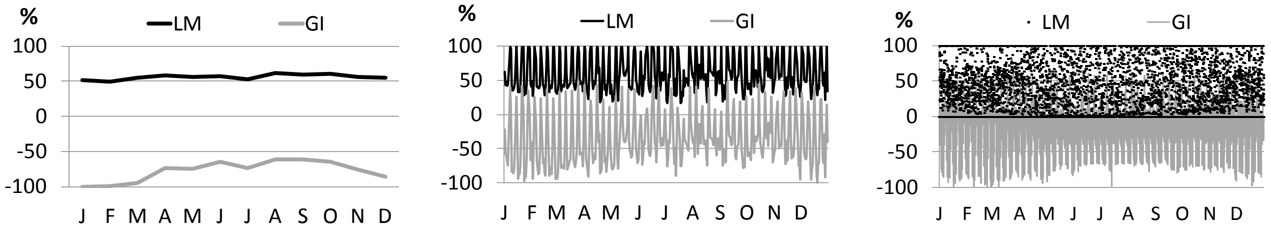
(d) (e) (f)

Figure A.15: Load match (LM) and grid interaction (GI) for T4 in monthly (d), daily (e) and hourly (f) profiles for East-West facade in Florianopolis.



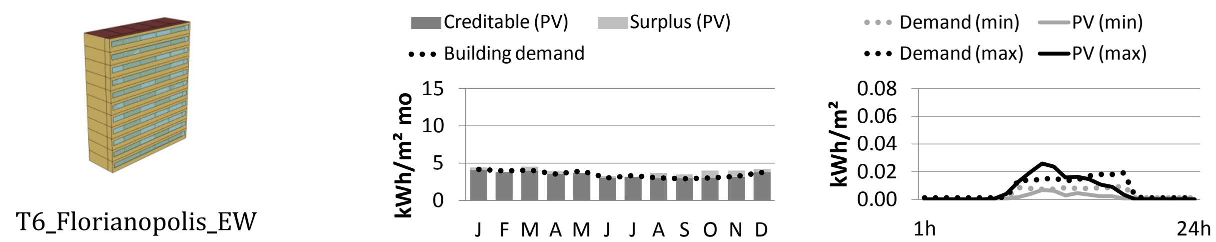
(a) (b) (c)

Figure A.16: Building demand and generated energy for T5 (a) in monthly (b) and daily (c) profiles for East-West facade in Florianopolis.



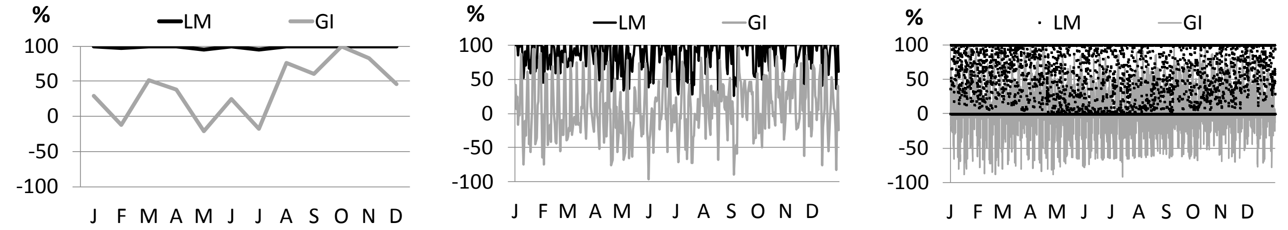
(d) (e) (f)

Figure A.17: Load match (LM) and grid interaction (GI) for T5 in monthly (d), daily (e) and hourly (f) profiles for East-West facade in Florianopolis.



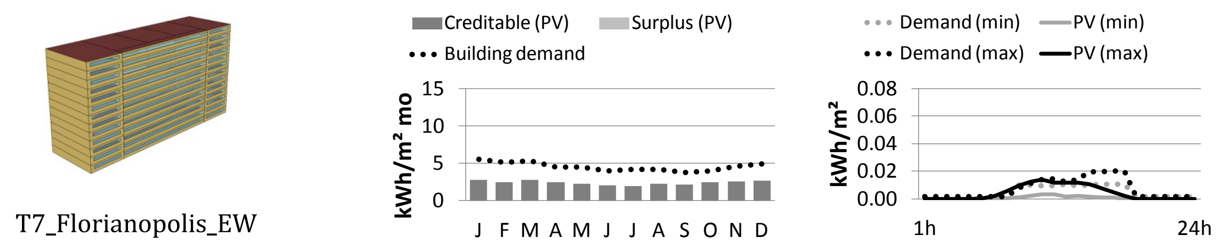
(a) (b) (c)

Figure A.18: Building demand and generated energy for T6 (a) in monthly (b) and daily (c) profiles for East-West facade in Florianopolis.



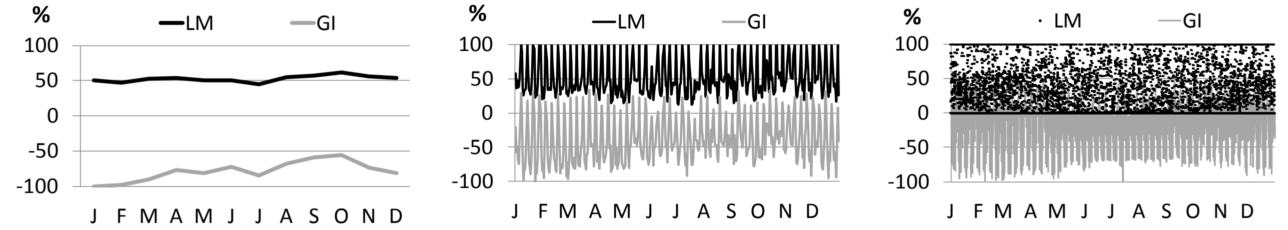
(d) (e) (f)

Figure A.19: Load match (LM) and grid interaction (GI) for T6 in monthly (d), daily (e) and hourly (f) profiles for East-West facade in Florianopolis.



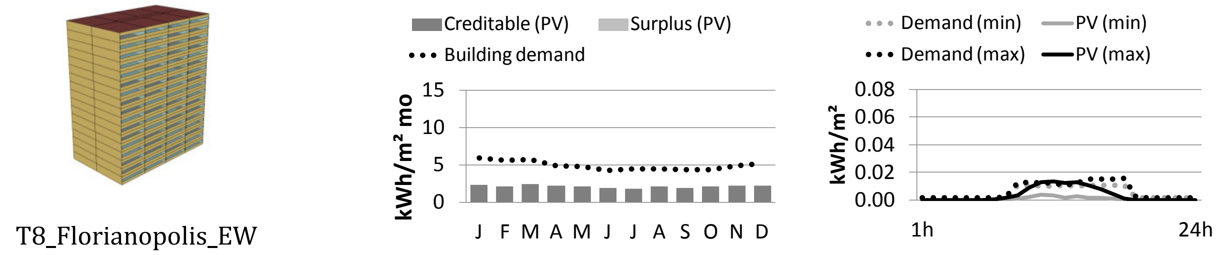
(a) (b) (c)

Figure A.20: Building demand and generated energy for T7 (a) in monthly (b) and daily (c) profiles for East-West facade in Florianopolis.



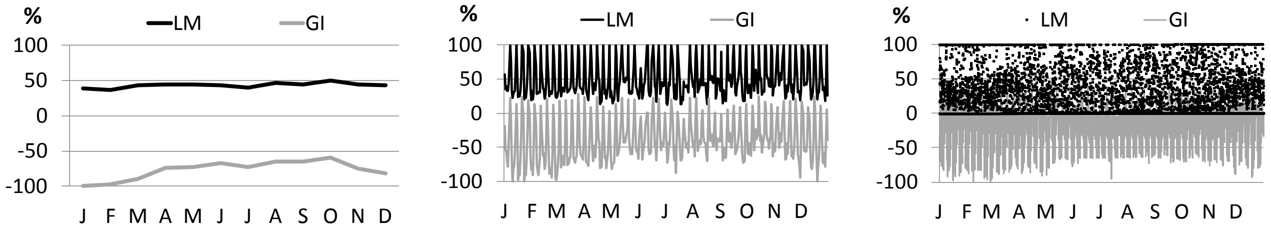
(d) (e) (f)

Figure A.21: Load match (LM) and grid interaction (GI) for T7 in monthly (d), daily (e) and hourly (f) profiles for East-West facade in Florianopolis.



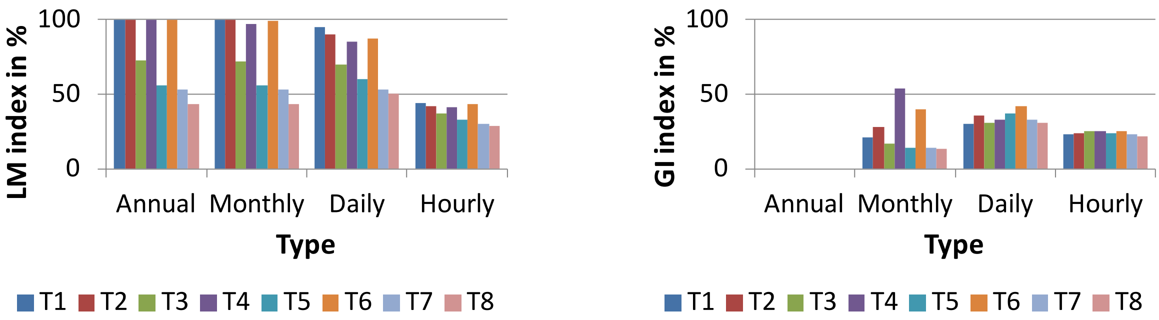
(a) (b) (c)

Figure A.22: Building demand and generated energy for T8 (a) in monthly (b) and daily (c) profiles for East-West facade in Florianopolis.



(d) (e) (f)

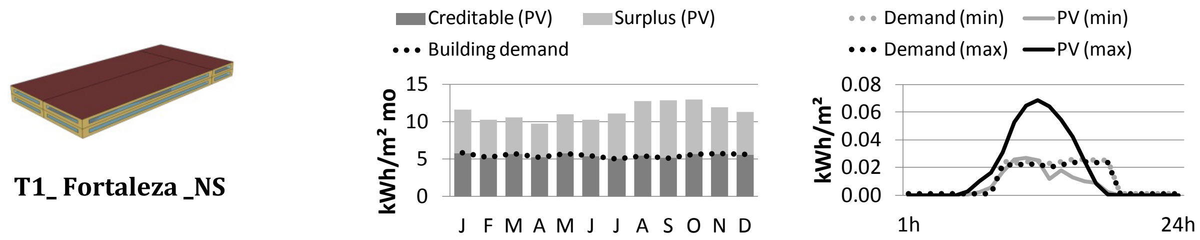
Figure A.23: Load match (LM) and grid interaction (GI) for T8 in monthly (d), daily (e) and hourly (f) profiles for East-West facade in Florianopolis.



(a) (b)

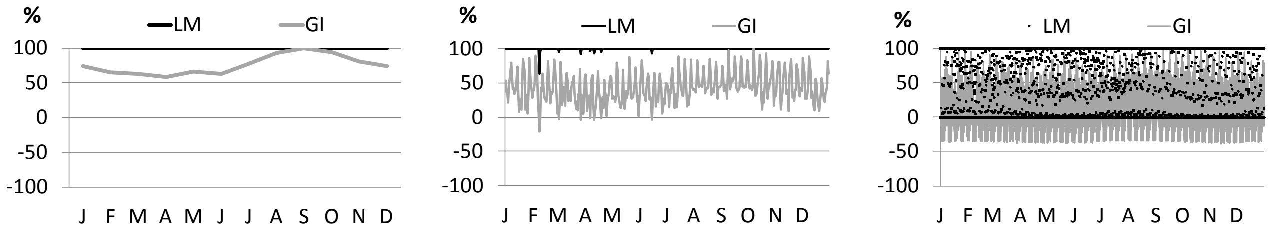
Figure A.24: Comparison of the load matching (a) and grid interaction (b) indices based on different time resolutions for the eight types in Florianopolis, with East-West orientation.

North-South orientation for Fortaleza



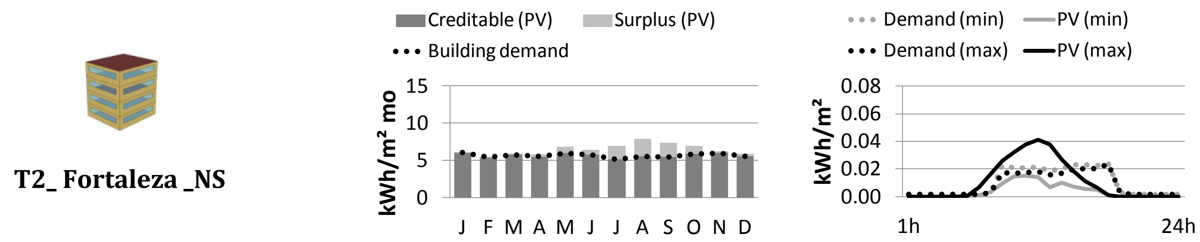
(a) (b) (c)

Figure A.25: Building demand and generated energy for T1 (a) in monthly (b) and daily (c) profiles for North-South facade in Fortaleza.



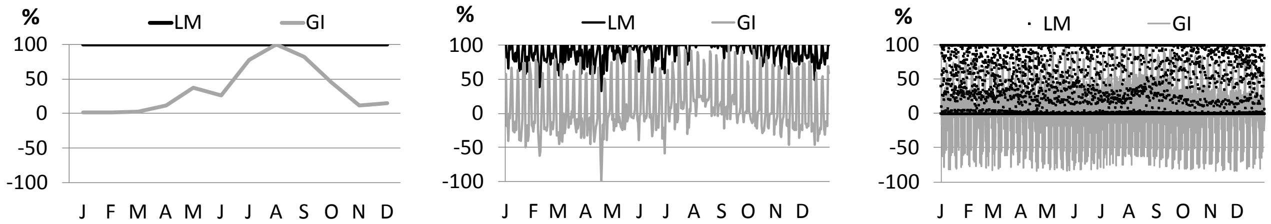
(d) (e) (f)

Figure A.26: Load match (LM) and grid interaction (GI) for T1 in monthly (d), daily (e) and hourly (f) profiles for North-South facade in Fortaleza.



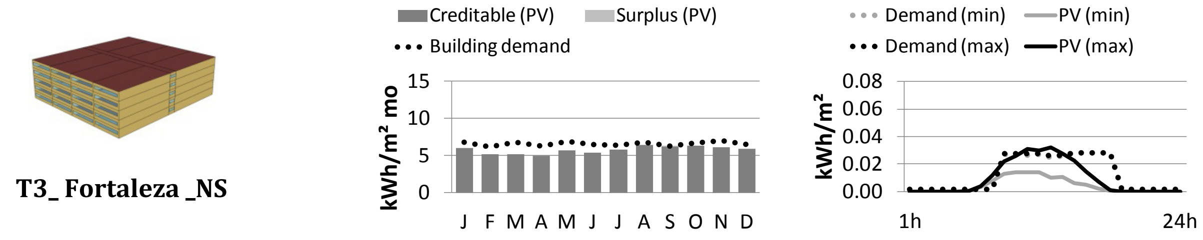
(a) (b) (c)

Figure A.27: Building demand and generated energy for T2 (a) in monthly (b) and daily (c) profiles for North-South facade in Fortaleza.



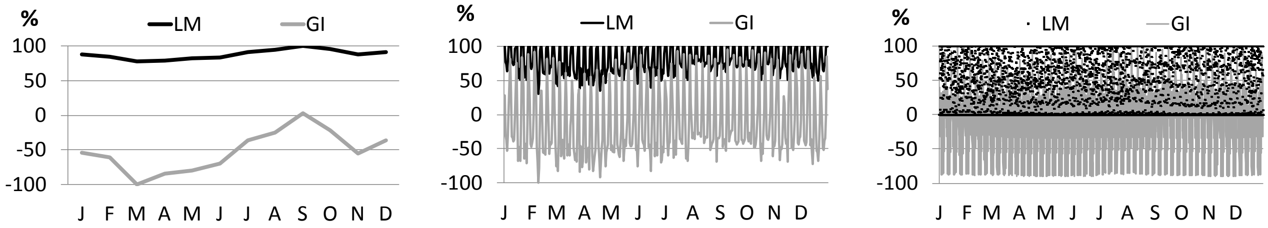
(d) (e) (f)

Figure A.28: Load match (LM) and grid interaction (GI) for T2 in monthly (d), daily (e) and hourly (f) profiles for North-South facade in Fortaleza.



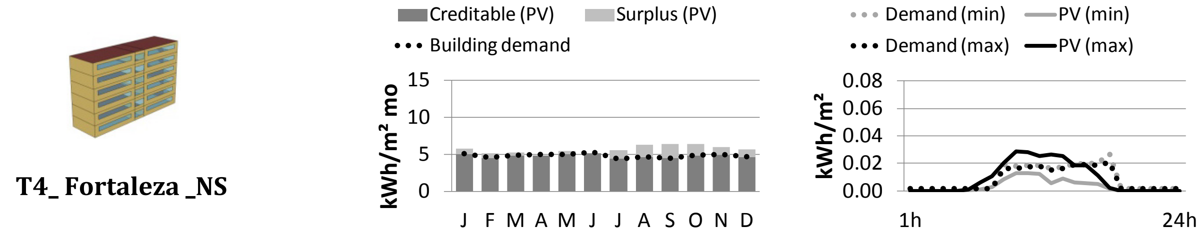
(a) (b) (c)

Figure A.29: Building demand and generated energy for T3 (a) in monthly (b) and daily (c) profiles for North-South facade in Fortaleza.



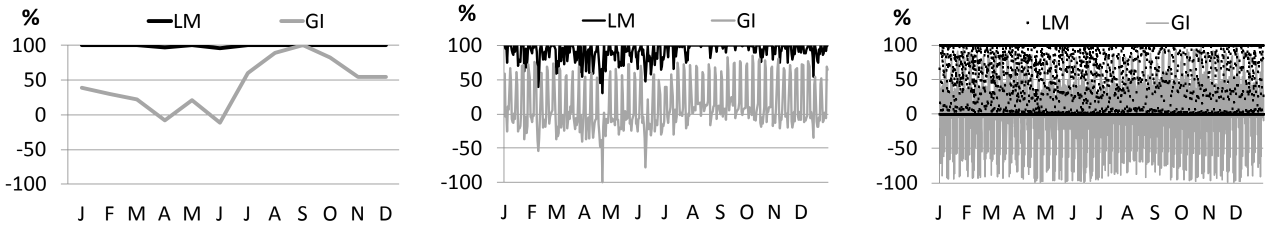
(d) (e) (f)

Figure A.30: Load match (LM) and grid interaction (GI) for T3 in monthly (d), daily (e) and hourly (f) profiles for North-South facade in Fortaleza.



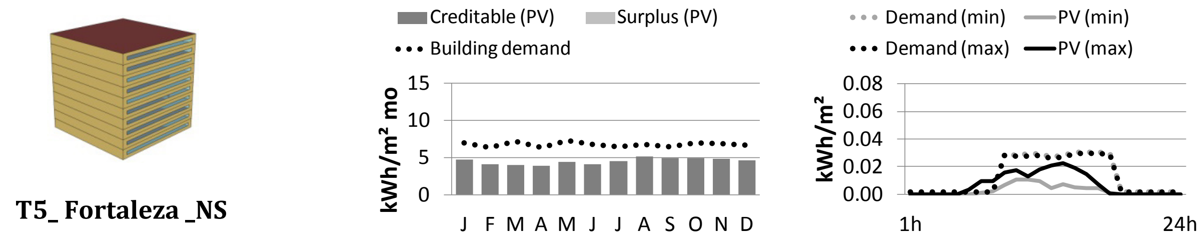
(a) (b) (c)

Figure A.31: Building demand and generated energy for T4 (a) in monthly (b) and daily (c) profiles for North-South facade in Fortaleza.



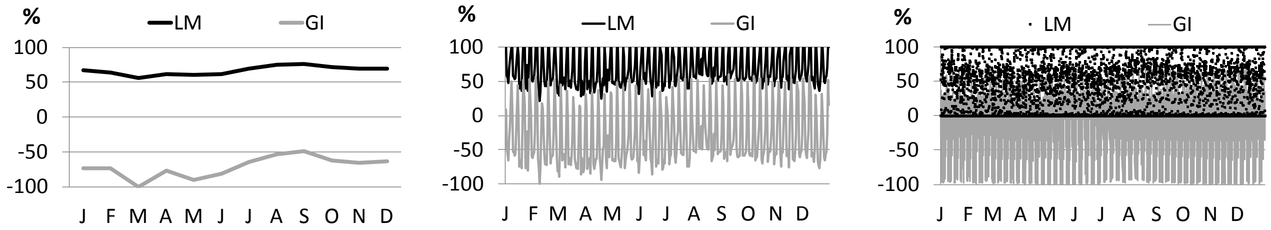
(d) (e) (f)

Figure A.32: Load match (LM) and grid interaction (GI) for T4 in monthly (d), daily (e) and hourly (f) profiles for North-South facade in Fortaleza.



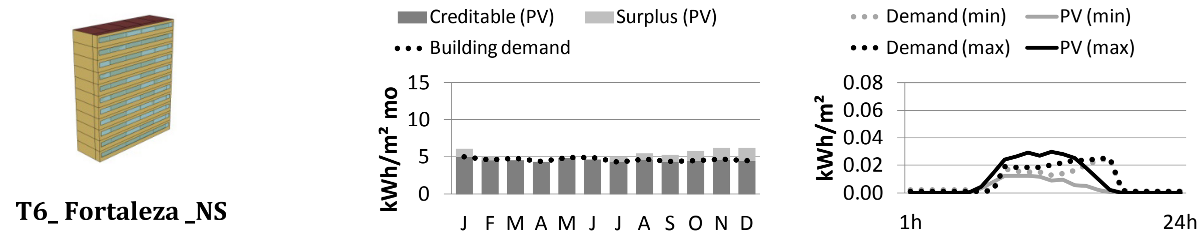
(a) (b) (c)

Figure A.33: Building demand and generated energy for T5 (a) in monthly (b) and daily (c) profiles for North-South facade in Fortaleza.



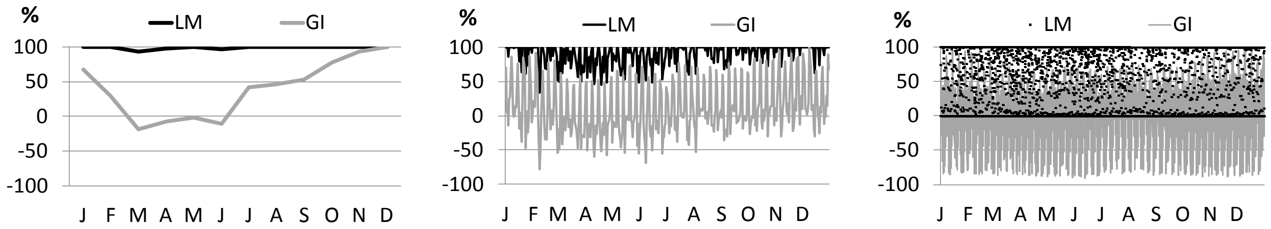
(d) (e) (f)

Figure A.34: Load match (LM) and grid interaction (GI) for T5 in monthly (d), daily (e) and hourly (f) profiles for North-South facade in Fortaleza.



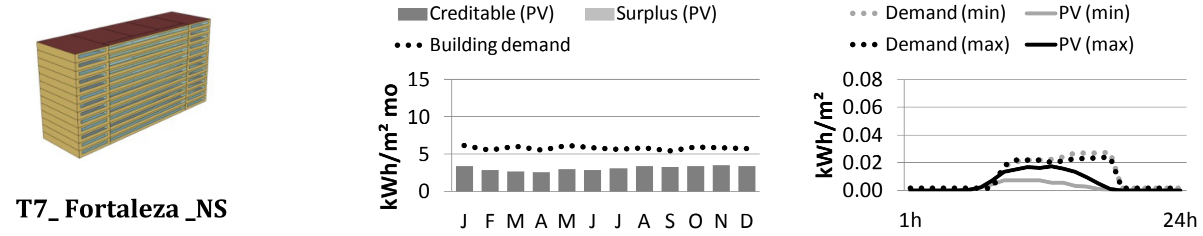
(a) (b) (c)

Figure A.35: Building demand and generated energy for T6 (a) in monthly (b) and daily (c) profiles for North-South facade in Fortaleza.



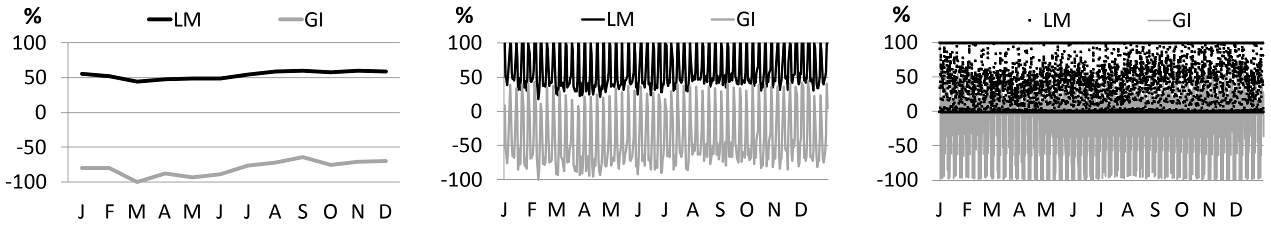
(d) (e) (f)

Figure A.36: Load match (LM) and grid interaction (GI) for T6 in monthly (d), daily (e) and hourly (f) profiles for North-South facade in Fortaleza.



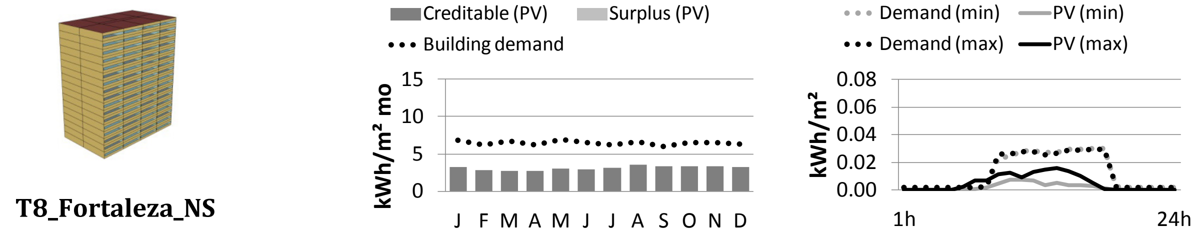
(a) (b) (c)

Figure A.37: Building demand and generated energy for T7 (a) in monthly (b) and daily (c) profiles for North-South facade in Fortaleza.



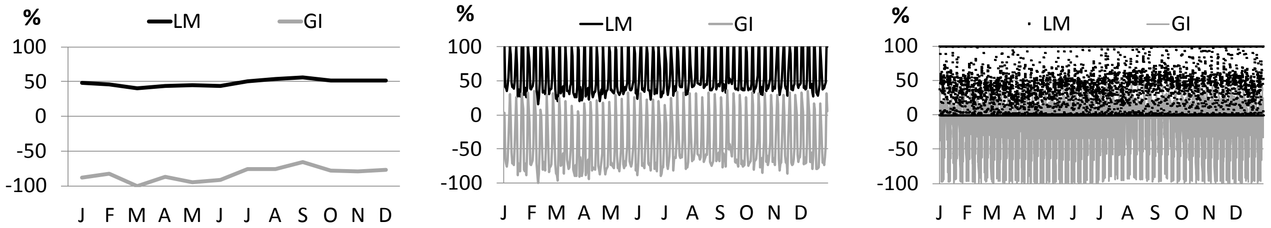
(d) (e) (f)

Figure A.38: Load match (LM) and grid interaction (GI) for T7 in monthly (d), daily (e) and hourly (f) profiles for North-South facade in Fortaleza.



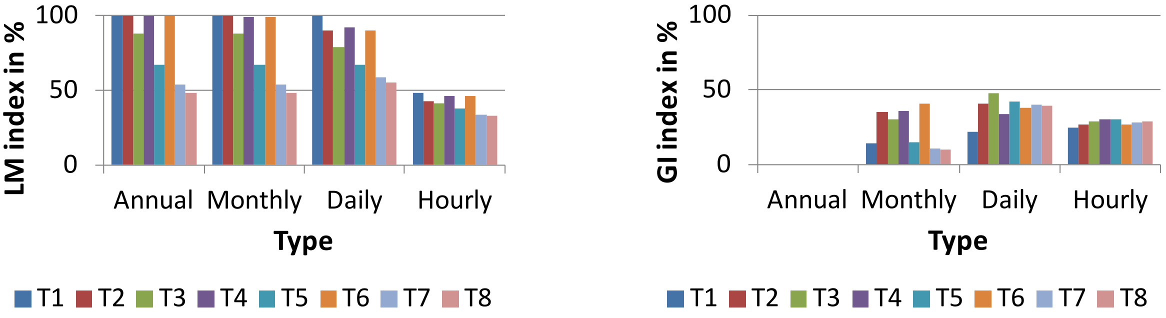
(a) (b) (c)

Figure A.39: Building demand and generated energy for T8 (a) in monthly (b) and daily (c) profiles for North-South facade in Fortaleza.



(d) (e) (f)

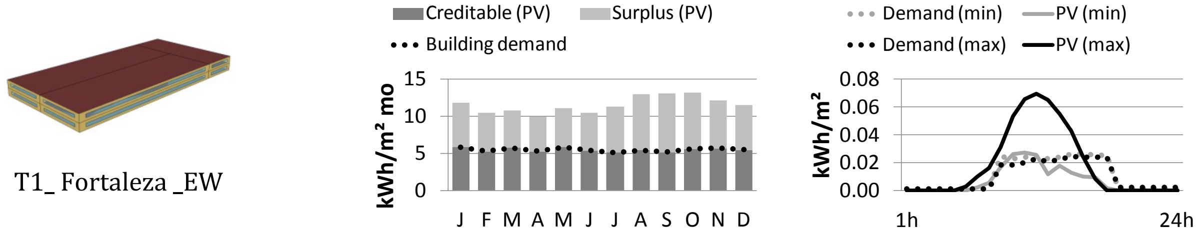
Figure A.40: Load match (LM) and grid interaction (GI) for T8 in monthly (d), daily (e) and hourly (f) profiles for North-South facade in Fortaleza.



(a) (b)

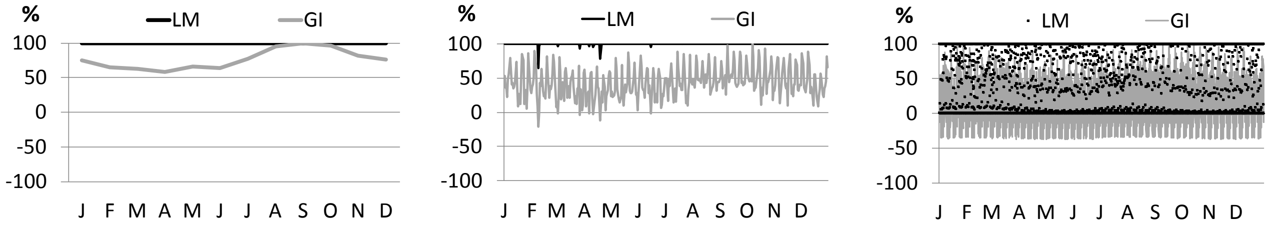
Figure A.41: Comparison of the load match (a) and grid interaction (b) indices based on different time resolutions for the eight types in Fortaleza, with North-South orientation.

East-West orientation for Fortaleza



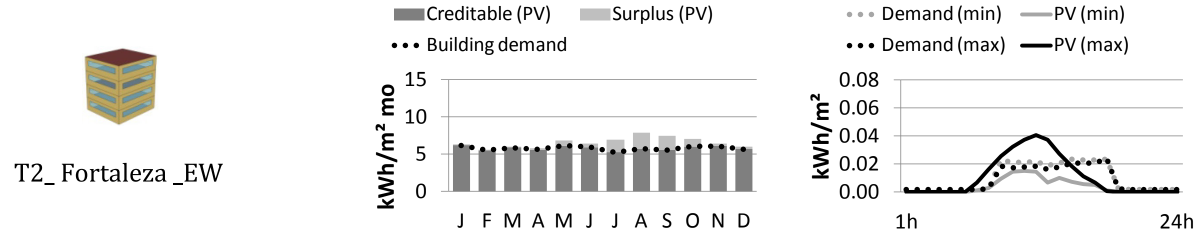
(a) (b) (c)

Figure A.42: Building demand and generated energy for T1 (a) in monthly (b) and daily (c) profiles for East-West facade in Fortaleza.



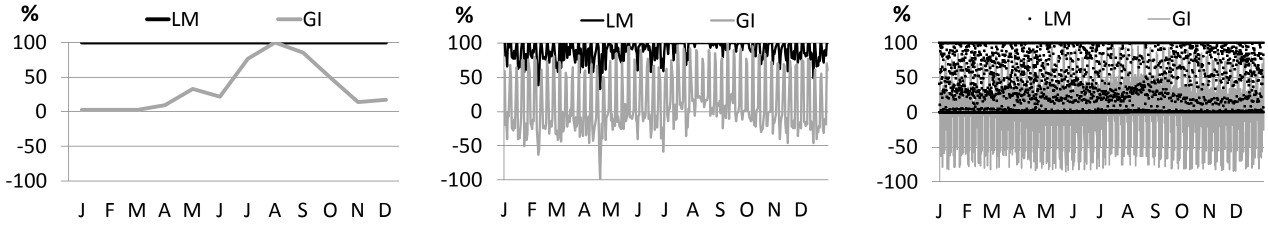
(d) (e) (f)

Figure A.43: Load match (LM) and grid interaction (GI) for T1 in monthly (d), daily (e) and hourly (f) profiles for East-West facade in Fortaleza.



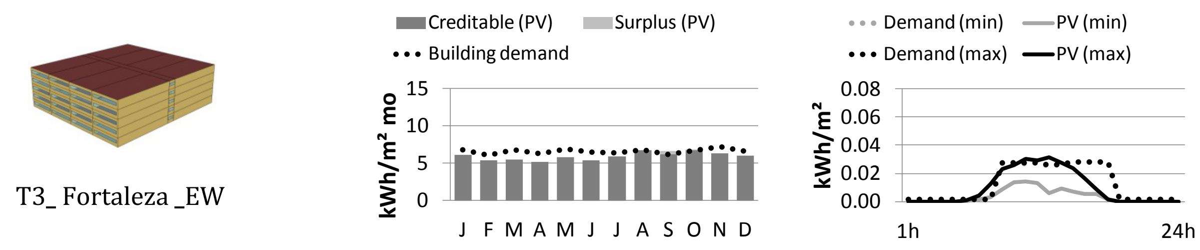
(a) (b) (c)

Figure A.44: Building demand and generated energy for T2 (a) in monthly (b) and daily (c) profiles for East-West facade in Fortaleza.



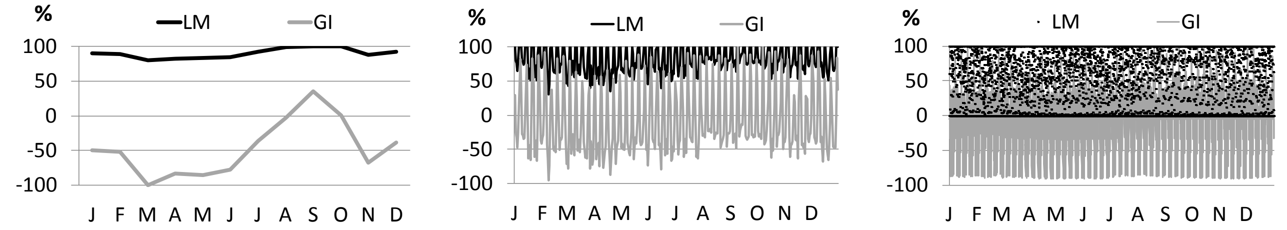
(d) (e) (f)

Figure A.45: Load match (LM) and grid interaction (GI) for T2 in monthly (d), daily (e) and hourly (f) profiles for North-South-West facade in Fortaleza.



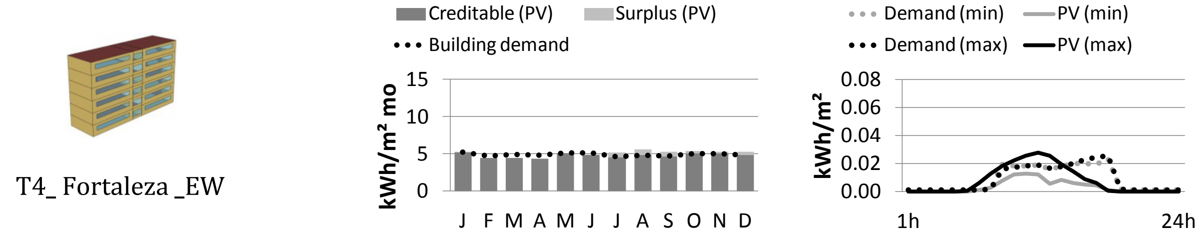
(a) (b) (c)

Figure A.46: Building demand and generated energy for T3 (a) in monthly (b) and daily (c) profiles for East-West facade in Fortaleza.



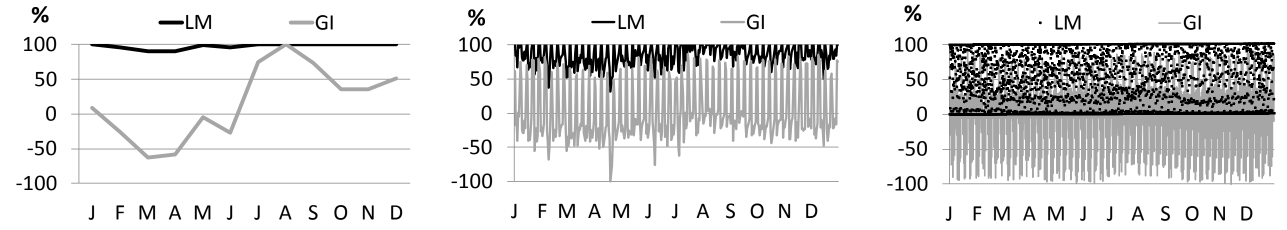
(d) (e) (f)

Figure A.47: Load match (LM) and grid interaction (GI) for T3 in monthly (d), daily (e) and hourly (f) profiles for North-South-West facade in Fortaleza.



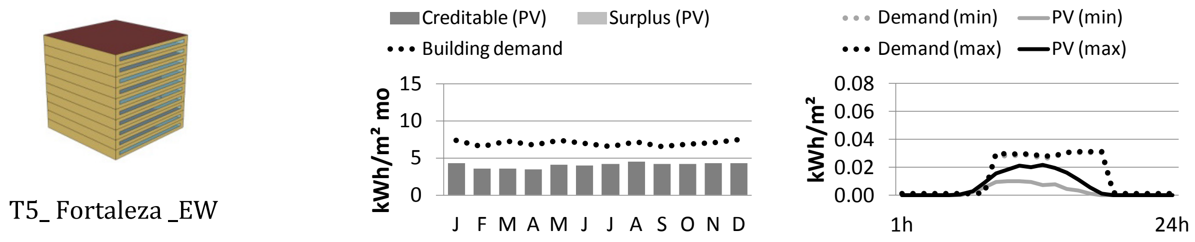
(a) (b) (c)

Figure A.48: Building demand and generated energy for T4 (a) in monthly (b) and daily (c) profiles for East-West facade in Fortaleza.



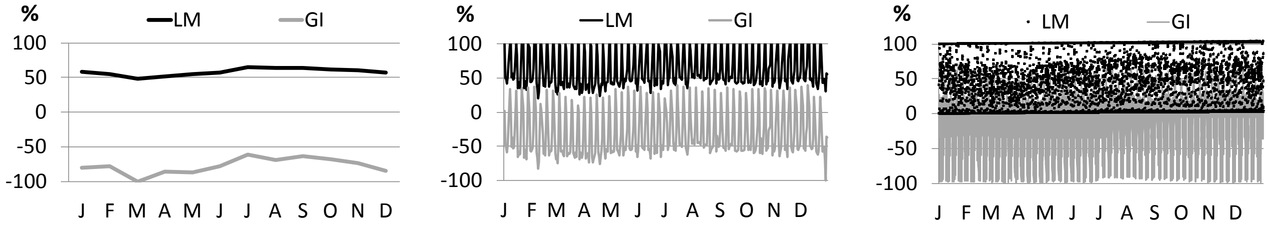
(d) (e) (f)

Figure A.49: Load match (LM) and grid interaction (GI) for T4 in monthly (d), daily (e) and hourly (f) profiles for North-South-West facade in Fortaleza.



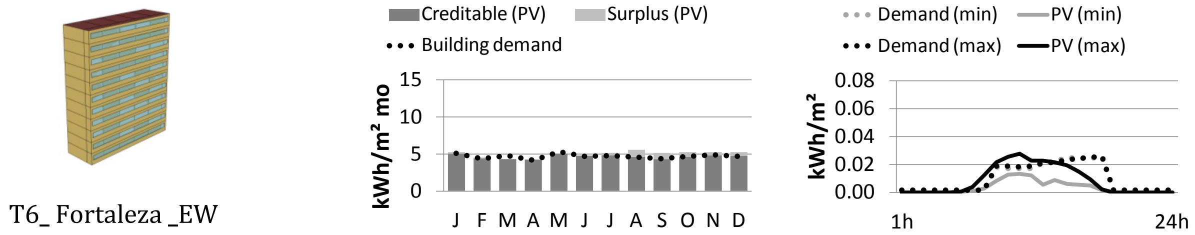
(a) (b) (c)

Figure A.50: Building demand and generated energy for T5 (a) in monthly (b) and daily (c) profiles for East-West facade in Fortaleza.



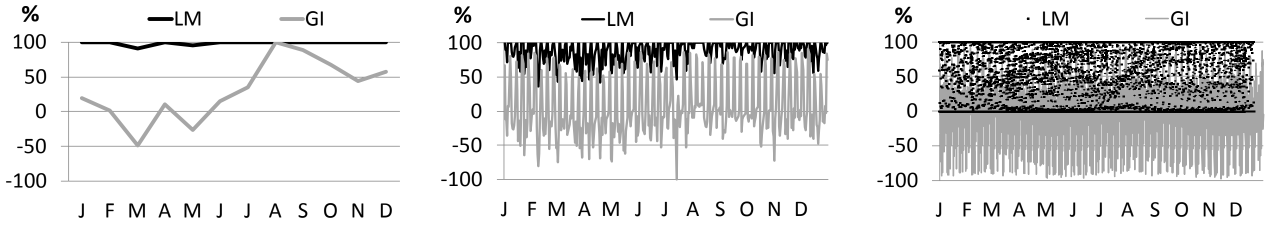
(d) (e) (f)

Figure A.51: Load match (LM) and grid interaction (GI) for T5 in monthly (d), daily (e) and hourly (f) profiles for North-South-West facade in Fortaleza.



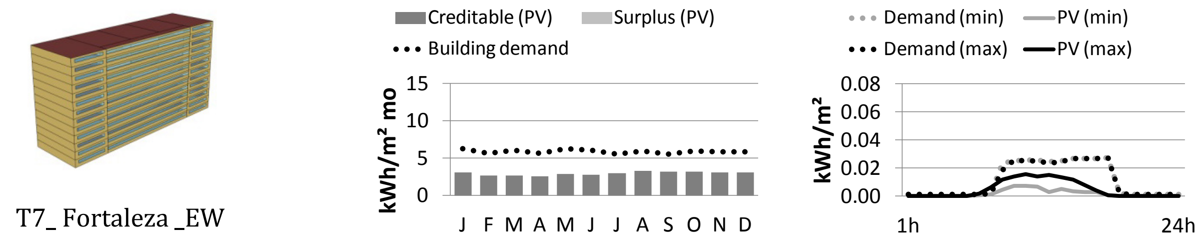
(a) (b) (c)

Figure A.52: Building demand and generated energy for T6 (a) in monthly (b) and daily (c) profiles for East-West facade in Fortaleza.



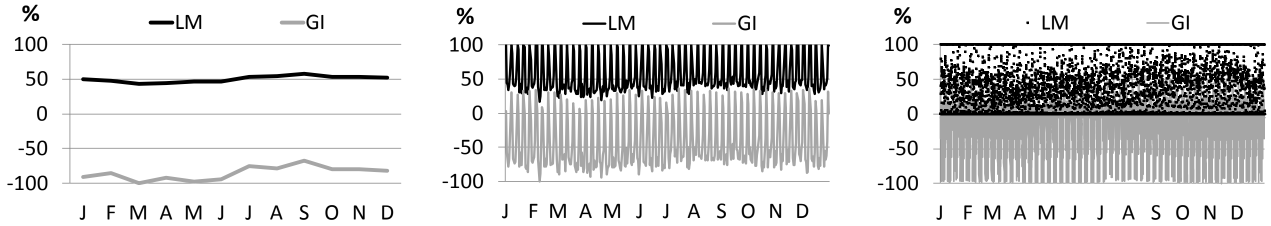
(d) (e) (f)

Figure A.53: Load match (LM) and grid interaction (GI) for T6 in monthly (d), daily (e) and hourly (f) profiles for North-South-West facade in Fortaleza.



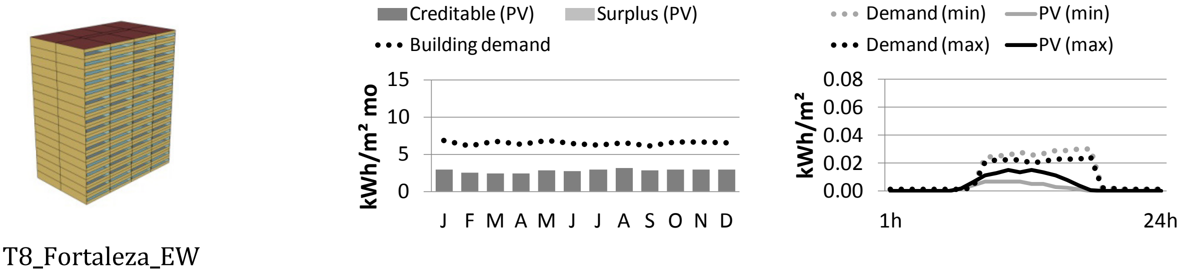
(a) (b) (c)

Figure A.54: Building demand and generated energy for T7 (a) in monthly (b) and daily (c) profiles for East-West facade in Fortaleza.



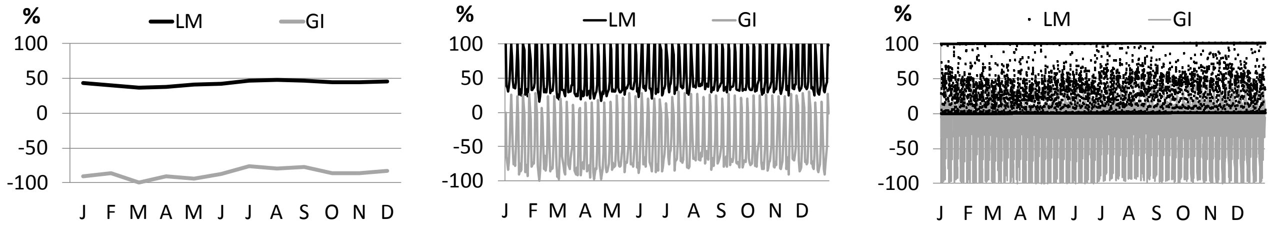
(d) (e) (f)

Figure A.55: Load match (LM) and grid interaction (GI) for T7 in monthly (d), daily (e) and hourly (f) profiles for North-South-West facade in Fortaleza.



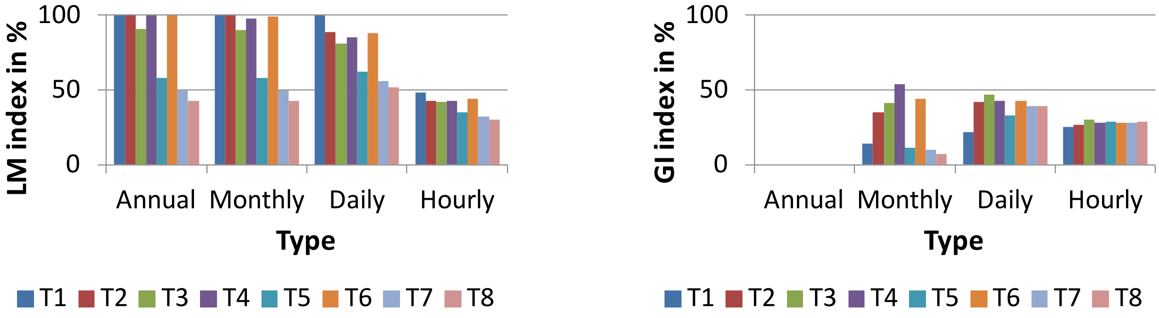
(a) (b) (c)

Figure A.56: Building demand and generated energy for T8 (a) in monthly (b) and daily (c) profiles for East-West facade in Fortaleza.



(d) (e) (f)

Figure A.57: Load match (LM) and grid interaction (GI) for T8 in monthly (d), daily (e) and hourly (f) profiles for North-South-West facade in Fortaleza.



(a) (b)

Figure A.58: Comparison of the load matching (a) and grid interaction (b) indices based on different time resolutions for the eight types in Fortaleza, with East-West orientation.

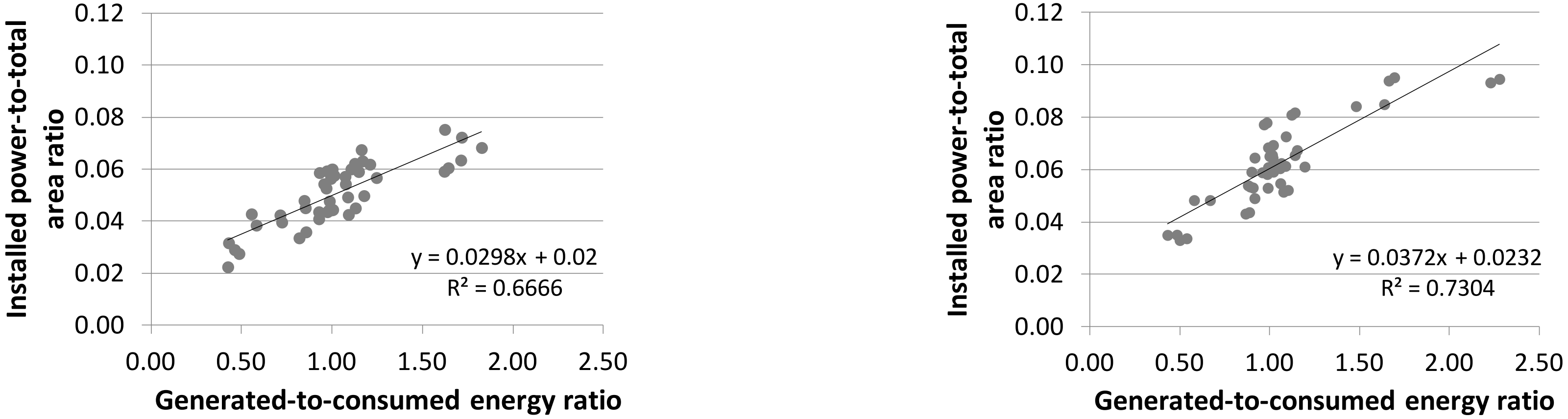
A.6 Electric energy balance - ZEB study

Table A.11 presents the energy demand and generated energy for all types with different numbers of storeys. The gray color represents the models which reached zero energy balance.

Tipology	**Florianopolis - Electricity in kWh/(m^2 y)**								**Fortaleza - Electricity in kWh/(m^2 y)**							
	North-South				**East-West**				**North-South**				**East-West**			
	Storey	Load	Generation	Plus	Storey	Load	Generation	Plus	Storey	Load	Generation	Plus	Storey	Load	Generation	Plus
	4	52.49	43.05	0.00	4	52.89	45.38	0.00	5	71.13	61.55	0.00	5	71.45	63.29	0.00
T1	3	52.12	56.96	4.84	3	52.42	59.30	6.88	4	70.50	75.86	5.36	4	70.84	78.01	7.18
	2	50.31	82.73	32.41	2	50.63	86.76	36.13	2	65.66	146.29	80.62	2	65.82	149.89	84.08
	7	46.22	45.97	0.00	7	46.14	44.89	0.00	7	70.05	67.79	0.00	7	70.07	68.87	0.00
T2	6	46.18	53.05	6.86	6	46.04	51.89	5.85	6	69.74	78.20	8.46	6	69.76	79.48	9.73
	4	45.60	83.38	37.78	4	45.53	78.21	32.68	4	68.23	113.41	45.18	4	68.26	115.53	47.28
	5	62.67	44.80	0.00	5	62.71	45.42	0.00	5	78.86	69.33	0.00	5	78.99	71.56	0.00
T3	4	62.34	52.87	0.00	4	62.38	53.30	0.00	4	78.30	83.31	5.01	4	78.42	85.24	6.81
	3	61.74	66.31	4.57	3	61.78	66.50	4.72								
	29	38.60	37.93	0.00	35	40.27	40.23	0.00	20	58.86	58.80	0.00	14	60.59	60.06	0.00
T4	28	38.59	38.61	0.01	34	40.26	40.39	0.12	19	58.83	59.60	0.77	13	60.51	61.64	1.12
	6	38.22	61.99	23.77	6	39.67	64.45	24.77	6	57.49	94.12	36.63	6	59.31	87.76	28.45
	10	63.59	37.09	0.00	10	63.96	35.60	0.00	10	80.93	54.04	0.00	10	83.70	48.46	0.00
T5	4	62.74	60.05	0.00	4	63.11	58.85	0.00	6	80.24	72.10	0.00	5	82.36	75.44	0.00
	3	62.22	72.81	10.59	3	62.86	73.15	10.29	5	79.85	81.14	1.29	4	81.61	88.93	7.31
	12	40.94	39.94	0.00	16	41.84	41.71	0.00	16	56.08	55.59	0.00	13	56.71	55.89	0.00
T6	11	40.90	41.14	0.25	15	41.82	42.36	0.54	15	56.02	56.75	0.73	12	56.62	57.64	1.02
					11	41.71	46.18	4.47	11	55.69	63.46	7.78	11	56.51	59.71	3.21
	13	54.8	23.3	0.00	13	54.50	25.27	0.00	13	70.18	37.72	0.00	13	70.66	35.27	0.00
T7	4	53.8	50.0	0.00	4	53.58	52.91	0.00	6	69.30	63.44	0.00	5	69.41	68.65	0.00
	3	53.4	62.9	9.5	3	53.09	66.22	13.13	5	68.93	73.00	4.07	4	68.85	82.21	13.37
	17	53.59	26.14	0.00	17	58.40	25.15	0.00	17	77.58	37.49	0.00	17	77.79	33.53	0.00
T8	5	53.13	49.34	0.00	4	57.63	55.87	0.00	6	76.45	68.08	0.00	5	76.32	73.15	0.00
	4	52.87	57.56	4.69	3	57.19	69.27	12.07	5	76.08	77.55	1.47	4	75.69	87.18	11.49

Table A.11: Energy demand and generated energy for all building types in kWh/(m^2 y).

Figure A.59 presents the correlation between installed PV power to total area ratio and generated to consumed energy ratio for Florianopolis and Fortaleza.



(a) (b)

Figure A.59: Correlation considering all models described in Table A.11 for Florianopolis (a) and Fortaleza (b).

A.7 Average solar radiation for each storey and surface

Type T1: results in kWh/(m² y) for North-South (NS) and East-West (EW) orientations in Florianopolis and Fortaleza

T1_NS	**Florianopolis**											**Fortaleza**										
Surface	**Urban context**											**Urban context**										
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Roof	1630	1545	1464	1567	1508	1455	1498	1406	1585	1447	1471	2398	2325	2222	2337	2218	2100	2331	2092	2338	2199	2168
Number of storeys: North facade																						
2	1018	665	524	822	777	690	486	565	874	497	850	847	658	656	718	683	666	635	621	746	634	715
1	997	595	520	794	750	620	482	550	867	492	844	821	641	646	697	663	652	623	609	729	627	698
Number of storeys: East facade																						
2	857	568	476	576	450	459	636	461	722	547	490	1230	900	584	772	590	561	1049	557	1114	846	620
1	821	543	460	548	424	442	591	444	700	526	476	1192	877	540	650	561	517	1009	513	1086	824	594
Number of storeys: South facade																						
2	434	372	381	381	328	306	363	301	387	301	320	789	688	724	713	588	573	670	549	716	534	583
1	399	344	352	352	302	280	335	277	359	276	296	761	663	702	695	568	554	650	531	696	522	569
Number of storeys: West facade																						
2	853	618	738	711	581	447	738	390	585	471	396	1304	1032	1121	1216	986	640	1094	625	870	654	641
1	818	590	692	681	544	420	694	373	564	455	375	1269	988	1053	1190	874	615	1027	602	848	633	615

Selected contexts	Solar irradiation level in kWh/(m² y)
■ Uniform and Random	▨ Roof and Facade

Table A.12: Type T1 for North-South orientation in Florianopolis and Fortaleza.

T1_EW	Florianopolis											Fortaleza										
Surface	**Urban context**											**Urban context**										
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Roof	1630	1520	1427	1542	1451	1336	1538	1328	1553	1442	1372	2398	2283	2079	2306	2101	1881	2314	1920	2292	2143	2002
Number of storeys: North facade																						
2	1022	676	605	815	758	752	545	613	884	599	814	852	652	669	718	675	686	645	639	748	662	699
1	1000	610	602	800	739	682	539	611	870	588	804	824	638	661	700	657	668	632	630	730	652	682
Number of storeys: East facade																						
2	853	528	393	508	403	397	667	395	671	517	429	1228	860	516	709	548	496	1064	499	1074	834	555
1	817	506	371	477	375	377	637	376	648	497	406	1190	837	464	581	522	448	1036	452	1038	813	530
Number of storeys: South facade																						
2	435	368	375	380	320	297	347	297	375	301	316	793	683	724	720	596	565	641	552	703	543	591
1	401	340	349	349	295	275	320	277	348	280	294	766	660	702	697	578	548	624	539	682	534	579
Number of storeys: West facade																						
2	849	606	689	767	599	395	690	386	542	430	372	1302	1016	1060	1247	986	580	1060	596	838	609	590
1	814	584	662	743	557	368	666	365	516	409	347	1267	964	1015	1223	863	558	1017	575	817	588	565

Selected contexts Solar irradiation level in kWh/(m^2 y)

■ Uniform and Random ▨ Roof and Facade

Table A.13: Type T1 for East-West orientation in Florianopolis and Fortaleza.

Type T2: results in kWh/(m^2 y) for North-South (NS) and East-West (EW) orientations in Florianopolis and Fortaleza

T2_NS	**Florianopolis**											**Fortaleza**										
Surface	**Urban context**											**Urban context**										
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Roof	1630	714	803	1035	680	578	768	526	929	587	679	2398	1284	1351	1647	1048	865	1392	797	1415	862	943
Number of storeys: North facade																						
4	860	119	229	290	134	176	169	158	263	136	361	688	182	263	321	189	235	218	207	309	178	325
3	699	99	202	263	118	155	160	148	206	125	335	602	157	242	296	173	212	199	185	268	163	298
2	496	92	178	246	111	144	150	142	171	116	298	540	145	222	280	167	199	187	176	242	152	269
1	392	87	164	222	105	138	145	140	157	113	245	487	144	215	274	169	196	189	180	222	156	244
Number of storeys: East facade																						
4	707	149	185	286	103	155	239	153	267	106	125	1062	269	260	353	167	210	546	213	439	169	184
3	524	133	158	266	91	148	163	135	244	96	112	844	230	234	319	150	200	273	192	395	144	167
2	392	114	135	242	83	138	133	119	202	85	102	562	202	210	281	136	188	223	176	335	127	153
1	308	98	119	219	75	129	105	108	159	80	92	425	182	187	252	122	174	173	166	278	119	143
Number of storeys: South facade																						
4	358	153	203	197	114	96	132	90	192	84	104	637	295	404	366	153	111	231	166	326	111	176
3	295	138	181	172	103	88	120	84	170	77	95	555	263	367	335	140	107	213	162	292	98	167
2	250	126	155	153	95	82	109	80	145	73	87	502	221	333	303	129	104	202	159	259	91	161
1	211	113	132	135	86	75	98	75	125	69	79	452	203	310	273	117	96	196	146	232	84	147
Number of storeys: West facade																						
4	705	141	255	417	140	92	197	106	165	121	94	1102	327	471	840	216	153	300	169	267	204	175
3	526	112	219	367	124	82	175	97	140	113	89	830	247	359	741	202	141	270	151	230	181	159
2	395	99	200	303	113	74	157	88	115	104	84	596	221	307	642	189	133	242	142	200	164	147
1	308	91	180	245	107	69	148	78	103	98	79	484	181	262	550	179	121	221	133	180	149	138

Selected contexts	Solar irradiation level in kWh/(m^2 y)
■ Uniform and Random	░ Roof and Facade

Table A.14: Type T2 for North-South orientation in Florianopolis and Fortaleza.

T2_EW	**Florianopolis**											**Fortaleza**										
Surface	**Urban context**											**Urban context**										
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Roof	1630	698	782	1029	671	576	806	524	909	583	655	2398	1239	1322	1640	1037	832	1405	784	1380	856	904
Number of storeys: North facade																						
4	862	120	236	295	136	184	171	168	274	142	360	689	180	253	318	192	248	216	222	313	183	325
3	703	100	207	268	120	164	161	154	206	129	334	603	157	235	292	177	229	202	200	272	170	298
2	505	93	186	253	113	154	152	145	170	122	302	541	149	222	279	173	220	191	185	243	165	273
1	403	89	166	230	107	143	145	144	157	118	247	492	147	212	271	173	211	190	191	224	162	247
Number of storeys: East facade																						
4	705	143	182	271	102	160	201	149	261	106	122	1060	256	248	339	164	201	371	204	423	165	173
3	520	127	155	251	89	150	159	132	238	95	109	839	219	222	303	147	190	247	184	378	140	157
2	388	110	131	228	82	141	130	114	200	84	100	556	192	199	269	133	180	213	171	329	123	146
1	303	96	115	205	75	131	98	102	160	79	90	418	174	178	236	121	168	169	157	275	117	137
Number of storeys: South facade																						
4	359	155	204	201	115	96	139	92	192	85	101	638	294	402	372	168	117	264	171	327	117	184
3	296	140	182	176	106	89	126	86	169	80	94	557	261	365	341	146	113	249	168	291	104	174
2	252	128	157	158	97	83	116	82	147	76	86	506	224	333	315	137	110	220	166	261	99	167
1	215	116	135	138	89	76	105	77	127	72	79	458	206	311	295	127	102	209	155	233	91	154
Number of storeys: West facade																						
4	702	143	240	426	133	93	250	105	156	117	91	1099	315	452	837	208	148	431	163	253	196	165
3	522	113	205	373	123	83	210	96	134	109	84	825	239	327	733	196	136	305	148	216	173	150
2	390	101	184	307	114	76	180	86	114	101	80	591	216	303	645	187	127	276	139	189	158	140
1	303	92	163	248	107	70	157	78	101	96	75	476	180	256	551	177	117	228	129	173	143	132

Selected contexts
Solar irradiation level in kWh/(m^2 y)

■ Uniform and Random
░ Roof and Facade

Table A.15: Type T2 for East-West orientation in Florianopolis and Fortaleza.

Type T3: results in kWh/(m^2 y) for North-South (NS) and East-West (EW) orientations in Florianopolis and Fortaleza

T3_NS	**Florianopolis**											**Fortaleza**										
Surface	**Urban context**											**Urban context**										
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Roof	1630	1568	1481	1581	1515	1439	1545	1415	1596	1496	1456	2398	2336	2187	2350	2216	2048	2352	2068	2352	2232	2156
Number of storeys: North facade																						
5	973	736	635	844	790	779	581	584	888	611	832	805	639	636	720	678	668	615	608	736	621	712
4	948	708	575	823	769	750	524	571	879	551	821	790	627	631	708	667	659	607	600	727	616	699
3	925	627	543	802	743	672	490	557	867	519	810	774	617	627	694	649	646	601	593	716	613	684
2	904	566	537	776	713	613	482	528	853	507	793	754	606	617	673	629	631	591	585	704	604	669
1	881	554	529	748	683	604	475	472	839	500	781	725	585	602	644	603	613	573	568	681	589	644
Number of storeys: East facade																						
5	828	609	445	568	434	440	689	439	722	591	483	1193	973	582	891	572	559	1082	559	1106	924	592
4	798	568	427	545	421	423	668	421	707	551	454	1168	876	530	866	559	507	1066	507	1088	827	577
3	755	529	411	517	399	414	627	412	691	509	441	1116	855	505	638	541	485	1045	485	1068	808	559
2	700	500	383	490	374	387	596	385	665	483	426	1061	829	485	598	498	467	1000	466	1047	785	539
1	655	471	366	459	345	370	558	370	637	460	404	1032	735	459	569	438	441	974	441	1023	699	515
Number of storeys: South facade																						
5	423	381	394	390	321	296	366	290	393	292	313	748	684	736	708	562	546	649	517	719	500	576
4	407	369	385	381	313	288	353	282	384	286	304	732	665	726	700	551	538	638	512	704	498	566
3	387	351	367	365	301	276	337	271	368	275	293	716	639	706	692	534	528	626	506	676	494	550
2	363	331	345	344	285	261	317	255	347	261	278	699	625	688	680	527	513	613	497	659	482	543
1	331	303	315	315	260	238	290	233	317	237	254	672	602	653	644	511	480	592	482	632	459	527

Continuing Table A.16

Number of storeys: West facade																						
5	824	627	732	763	654	428	722	407	617	477	385	1267	1052	1134	1249	1023	615	1112	609	937	632	616
4	796	605	714	745	623	416	708	376	581	444	373	1243	1037	1119	1236	988	598	1101	595	846	613	604
3	753	584	684	723	573	396	679	360	545	429	354	1150	1017	1103	1216	961	584	1087	578	826	598	585
2	702	556	663	698	528	371	658	345	518	410	337	1046	961	1025	1196	853	541	1009	559	804	581	540
1	656	529	636	671	492	344	631	327	486	390	312	1018	935	991	1172	795	456	976	539	757	562	456

Selected contexts	Solar irradiation level in kWh/(m^2 y)
■ Uniform and Random	▨ Roof and Facade

Table A.16: Type T3 for North-South orientation in Florianopolis and Fortaleza.

T3_EW	**Florianopolis**											**Fortaleza**										
Surface	**Urban context**											**Urban context**										
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Roof	1630	1564	1473	1578	1506	1419	1550	1402	1593	1496	1442	2398	2331	2169	2347	2198	2016	2351	2047	2347	2228	2135
Number of storeys: North facade																						
5	974	734	647	842	789	784	587	592	889	629	826	806	638	639	721	677	671	615	612	736	627	708
4	949	706	592	822	766	757	534	579	879	573	816	792	626	635	708	666	663	608	604	726	623	696
3	927	628	557	800	740	681	501	566	868	536	804	776	617	631	694	648	649	604	597	718	617	681
2	907	567	550	775	711	623	492	540	854	522	786	756	606	623	673	628	634	595	588	707	610	668
1	885	554	543	749	683	613	485	485	841	515	772	728	583	607	645	603	615	577	572	684	597	643
Number of storeys: East facade																						
5	826	607	433	559	424	432	696	429	712	589	475	1193	969	571	882	564	549	1082	551	1097	926	581
4	797	564	410	535	412	415	665	410	702	544	444	1167	871	519	860	552	497	1067	498	1083	828	567
3	753	523	400	506	391	405	635	401	681	507	432	1115	847	495	628	535	475	1047	475	1065	808	550
2	698	493	371	478	367	378	603	373	656	480	414	1060	818	474	587	491	457	1004	457	1043	785	530
1	652	465	355	447	338	362	567	359	629	456	392	1030	727	447	559	430	431	979	432	979	697	506

Continuing Table A.17

Number of storeys: South facade																						
5	423	380	392	391	321	296	366	289	390	293	312	748	682	734	711	564	544	651	516	718	502	579
4	407	367	383	382	312	287	353	281	381	286	304	733	662	723	702	552	537	639	511	703	499	568
3	387	350	365	367	300	275	337	270	365	276	293	718	640	704	696	537	528	627	506	674	495	551
2	364	331	343	344	283	260	318	255	345	262	278	701	628	689	681	532	511	615	498	659	483	547
1	332	302	314	315	258	239	290	233	315	238	254	674	604	652	644	516	479	593	482	633	459	530
Number of storeys: West facade																						
5	823	622	728	773	655	419	719	408	615	471	382	1266	1044	1123	1254	1017	603	1105	605	935	622	609
4	795	604	703	754	625	408	697	376	576	438	369	1241	1030	1108	1241	986	590	1093	592	842	608	597
3	751	580	680	734	576	387	675	360	539	422	350	1147	1014	1090	1221	962	576	1078	575	822	593	579
2	700	557	660	709	532	364	654	343	509	403	333	1042	957	1010	1201	855	531	998	556	801	575	533
1	653	531	633	682	495	337	628	324	479	382	307	1014	913	983	1178	797	446	972	537	753	556	448

Selected contexts Solar irradiation level in kWh/(m^2 y)

■ Uniform and Random ▨ Roof and Facade

Table A.17: Type T3 for East-West orientation in Florianopolis and Fortaleza.

Type T4: results in kWh/(m² y) for North-South (NS) and East-West (EW) orientations in Florianopolis and Fortaleza

T4_NS	Florianopolis											Fortaleza										
Surface	Urban context											Urban context										
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Roof	1630	1166	1014	1389	1178	996	1025	791	1235	875	1094	2398	2017	1760	2064	1608	1509	1908	1299	2089	1408	1523
Number of storeys: North facade																						
6	885	254	262	511	402	259	206	173	429	169	476	701	341	311	492	366	327	278	232	488	230	474
5	793	181	247	410	299	189	190	164	395	152	452	634	267	301	460	331	258	265	219	448	215	464
4	603	161	234	321	213	172	179	147	358	142	423	566	245	287	420	297	234	252	200	403	197	441
3	445	147	222	298	189	163	171	128	293	135	394	503	228	274	371	259	223	240	171	347	189	411
2	345	135	202	234	139	155	165	118	231	129	363	455	215	260	311	208	215	233	166	314	179	385
1	323	121	190	224	136	143	159	118	215	130	339	401	201	253	300	206	206	229	169	300	176	374
Number of storeys: East facade																						
6	756	317	335	462	189	226	378	217	450	227	284	1109	474	415	552	266	298	716	326	690	300	345
5	638	276	308	448	168	212	344	204	425	192	254	988	439	392	532	240	286	675	313	656	280	316
4	506	250	276	429	149	190	282	192	393	172	215	804	402	362	503	219	270	593	283	617	245	292
3	404	229	242	411	135	172	219	184	359	158	187	533	371	323	471	191	255	511	262	570	227	269
2	334	206	218	388	123	163	172	169	323	149	169	482	340	295	440	172	243	275	246	528	212	251
1	294	182	195	357	110	158	144	156	282	143	155	410	313	266	403	153	228	248	230	469	201	224
Number of storeys: South facade																						
6	371	258	278	293	184	169	204	130	296	135	173	648	472	544	508	251	237	404	191	533	167	261
5	322	230	264	266	167	153	181	119	279	123	157	588	435	522	472	235	222	366	164	507	159	244
4	270	202	244	230	146	134	159	107	255	110	137	521	396	487	429	219	195	326	154	472	143	228
3	231	175	213	195	128	116	143	96	224	100	120	473	373	440	394	206	161	306	144	428	132	211
2	200	155	186	171	114	102	132	89	193	92	107	429	341	404	369	196	139	289	141	390	127	200
1	167	138	160	152	101	90	115	81	166	83	95	397	316	383	348	181	125	268	125	365	117	189

Continuing Table A.18

Number of storeys: West facade																						
6	751	322	570	470	276	183	561	151	276	216	158	1181	642	956	957	554	266	851	236	455	312	298
5	640	293	536	451	239	165	531	140	239	198	147	975	601	904	916	436	240	804	217	414	280	284
4	511	246	481	424	199	146	483	125	222	173	136	801	529	734	863	365	220	683	203	376	248	263
3	406	202	427	395	178	128	430	117	209	159	126	607	458	641	814	278	192	598	183	330	231	230
2	334	167	376	362	145	116	371	112	188	143	121	552	324	495	741	231	177	456	175	293	211	216
1	293	145	338	296	131	106	334	105	169	129	113	456	295	463	613	215	156	423	163	257	190	202

Selected contexts	Solar irradiation level in kWh/(m^2 y)
■ Uniform and Random	□ Roof and Facade

Table A.18: Type T4 for North-South orientation in Florianopolis and Fortaleza.

T4_EW	**Florianopolis**											**Fortaleza**										
Surface	**Urban context**											**Urban context**										
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Roof	1630	1005	916	1258	946	772	1087	696	1176	915	752	2398	1579	1403	1851	1326	958	1732	966	1616	1288	1038
Number of storeys: North facade																						
6	897	222	301	483	348	413	229	346	527	286	458	714	304	334	476	363	453	285	358	479	328	407
5	817	181	281	407	286	376	213	327	484	254	446	658	246	318	447	339	400	263	343	448	313	394
4	681	167	266	340	224	353	201	300	438	227	403	599	224	296	413	310	376	244	329	416	295	373
3	536	154	251	323	207	340	193	284	382	213	371	536	211	278	384	292	365	234	310	391	281	354
2	443	145	240	284	167	321	168	249	308	199	346	497	207	267	336	248	357	229	291	371	268	331
1	398	136	226	272	160	299	167	237	258	192	328	461	206	258	326	240	344	226	289	348	254	312

Continuing Table A.19

Number of storeys: East facade																						
6	751	208	175	272	151	185	354	178	340	191	149	1113	291	267	387	221	201	513	213	454	247	199
5	606	176	162	249	135	177	320	166	315	160	135	963	259	243	353	201	190	475	199	438	215	173
4	451	159	146	219	119	168	271	153	294	145	119	747	235	214	313	179	177	419	184	416	192	157
3	342	143	132	193	105	160	227	142	263	133	110	435	216	189	259	158	166	367	168	385	177	145
2	271	126	121	168	94	151	190	132	227	123	105	383	201	169	217	139	157	287	157	338	165	130
1	229	113	113	148	84	143	156	123	192	114	98	295	186	150	190	122	145	233	146	295	153	120
Number of storeys: South facade																						
6	371	231	271	291	163	129	214	136	239	131	147	660	462	552	558	304	261	399	255	472	228	327
5	332	211	256	271	154	120	197	129	228	122	138	610	434	531	526	290	250	368	241	450	219	296
4	288	194	239	244	142	111	181	121	216	114	126	553	409	500	485	278	239	345	232	429	212	278
3	255	179	221	218	132	105	166	109	201	108	115	506	387	473	457	270	225	333	228	404	210	266
2	228	165	200	199	125	101	156	105	184	102	108	470	370	436	420	265	213	325	223	381	207	257
1	197	153	177	182	118	95	146	101	162	97	102	455	355	411	408	254	209	323	227	350	205	256
Number of storeys: West facade																						
6	749	257	327	635	259	129	328	132	235	179	116	1187	438	546	1047	418	164	555	191	315	262	187
5	607	223	298	587	228	114	300	119	198	165	107	934	405	512	967	355	151	518	163	269	228	171
4	453	186	257	527	189	100	262	102	180	143	98	726	336	443	929	267	139	451	151	247	206	158
3	343	156	222	468	159	90	227	93	164	126	90	484	286	395	798	223	127	401	138	228	183	146
2	270	133	198	402	135	83	200	84	150	111	84	431	234	328	707	203	119	323	128	205	164	134
1	229	121	184	344	126	76	184	76	136	99	77	320	216	262	657	194	109	250	120	189	146	123

Selected contexts	Solar irradiation level in kWh/(m^2 y)
■ Uniform and Random	▒ Roof and Facade

Table A.19: Type T4 for East-West orientation in Florianopolis and Fortaleza.

Type T5: results in kWh/(m^2 y) for North-South (NS) and East-West (EW) orientations in Florianopolis and Fortaleza

T5	Florianopolis											Fortaleza										
Surface	Urban context											Urban context										
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Roof	1630	1586	1499	1615	1534	1446	1582	1435	1610	1552	1475	2398	2353	2177	2385	2242	2047	2367	2083	2379	2272	2193
Number of storeys: North facade																						
10	916	822	653	923	873	881	591	729	913	643	817	729	662	617	770	723	707	590	604	762	609	697
9	868	775	621	896	838	841	562	688	901	600	799	696	627	602	739	686	673	570	580	745	592	683
8	821	726	549	871	801	798	487	585	883	528	781	665	595	587	719	657	645	554	557	719	575	668
7	769	679	514	835	753	756	450	529	862	495	766	627	564	570	692	627	618	535	537	696	558	653
6	700	620	501	792	711	692	432	498	836	479	751	602	537	555	659	595	588	518	519	673	540	641
5	569	496	485	750	660	569	413	424	802	456	729	580	508	531	629	564	564	494	503	652	521	622
4	527	458	463	708	606	531	384	399	759	421	704	550	488	490	607	535	540	452	487	635	475	596
3	449	407	431	621	526	483	352	389	730	384	686	531	474	460	588	515	529	422	473	618	442	573
2	415	356	420	554	452	430	348	379	697	373	673	512	461	452	574	498	518	415	453	601	433	557
1	400	348	411	537	431	418	347	352	670	364	658	490	440	442	555	481	507	401	403	577	418	533
Number of storeys: East facade																						
10	778	745	428	767	436	418	713	418	726	699	505	1136	1126	537	1139	559	507	1114	507	1093	1047	816
9	721	699	406	747	410	400	685	401	701	662	464	1070	1086	504	1115	535	474	1078	476	1076	1000	566
8	643	642	380	725	386	377	654	378	683	611	424	1000	996	486	1090	508	456	1058	460	1039	947	537
7	571	577	364	700	356	366	626	366	667	547	407	910	955	466	1057	436	441	1035	441	966	903	516
6	510	523	349	658	320	352	607	353	635	490	379	796	805	445	1023	410	424	1011	424	952	747	495
5	451	459	333	617	291	336	571	340	611	433	354	754	768	420	926	388	405	976	405	930	709	450
4	398	410	320	550	272	320	528	327	577	390	326	498	577	396	828	367	385	937	385	907	518	400
3	353	364	308	503	257	311	493	316	546	353	303	473	487	379	789	349	372	871	369	878	430	379
2	329	336	298	467	242	301	438	309	516	330	292	449	467	362	755	332	356	787	353	856	411	361
1	305	313	283	430	229	290	400	294	486	309	278	426	446	344	507	314	339	718	337	825	395	342

Continuing Table A.20

Number of storeys: South facade																						
10	387	405	396	409	305	297	394	270	391	273	305	673	726	730	730	528	543	712	482	717	457	542
9	361	391	388	399	292	280	376	257	382	261	289	642	694	720	720	503	513	684	459	699	436	528
8	338	379	382	390	278	261	359	243	377	248	275	613	662	712	706	478	484	645	442	680	418	514
7	313	361	373	378	263	243	341	230	369	237	260	588	642	704	692	467	460	620	428	671	407	501
6	293	335	362	364	249	227	318	218	358	225	245	554	614	693	671	457	424	593	408	657	382	483
5	272	308	345	343	234	211	294	205	341	212	229	526	585	678	644	445	397	559	396	634	365	459
4	254	285	323	319	220	195	273	193	321	199	214	511	559	657	626	434	381	529	385	610	352	449
3	239	268	304	300	209	183	255	183	302	188	201	502	541	619	599	424	372	514	377	591	343	442
2	226	252	285	280	197	172	238	173	282	177	189	484	530	599	587	411	367	505	372	569	335	426
1	206	228	257	253	180	158	217	159	254	160	172	451	513	573	570	372	358	475	362	542	311	393
Number of storeys: West facade																						
10	775	620	745	794	698	430	740	417	749	499	368	1208	1045	1211	1253	1079	599	1198	746	1160	776	592
9	718	592	729	780	675	405	721	376	711	459	347	1110	1023	1150	1243	1052	577	1131	572	1118	603	572
8	645	566	710	762	641	383	695	339	654	420	327	984	982	1107	1237	1025	547	1076	544	972	569	543
7	570	538	684	743	600	353	667	318	587	399	300	891	910	1084	1226	995	448	1054	522	925	549	446
6	511	506	662	712	556	321	644	296	525	372	274	787	884	1058	1209	947	425	1026	502	781	527	423
5	454	482	629	688	502	290	614	267	467	344	248	743	853	1023	1188	847	400	996	445	749	469	399
4	400	440	578	661	443	268	568	241	427	312	234	557	812	988	1160	736	378	959	373	599	395	380
3	354	410	542	638	401	250	538	217	395	279	221	530	749	899	1134	698	361	868	357	530	379	364
2	330	381	506	610	363	236	506	201	372	264	204	507	728	832	1102	663	344	804	342	511	361	348
1	304	357	469	572	323	224	475	189	351	248	191	485	678	761	996	502	325	737	323	492	343	330

Selected contexts — Solar irradiation level in kWh/(m^2 y)

■ Uniform and Random

▨ Roof and Facade

Table A.20: Type T5 for North-South and East-West orientation in Florianopolis and Fortaleza.

Type T6: results in kWh/(m² y) for North-South (NS) and East-West (EW) orientations in Florianopolis and Fortaleza

T6_NS	**Florianopolis**											**Fortaleza**										
Surface	**Urban context**											**Cases**										
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Roof	1630	1517	1250	1551	1402	1374	1290	1233	1494	1230	1327	2398	2278	2028	2320	2007	1820	2242	1754	2303	1976	1900
Number of storeys: North facade																						
11	878	776	343	879	765	791	290	414	629	293	714	688	599	403	720	642	613	368	427	607	360	534
10	782	686	330	855	737	695	272	293	602	271	653	617	532	383	701	612	543	346	395	598	336	517
9	580	537	315	820	693	549	255	264	544	251	590	542	464	361	657	562	478	320	342	586	312	502
8	411	389	300	756	618	404	238	198	496	228	570	471	410	342	593	494	423	301	263	568	291	492
7	316	267	273	663	529	284	217	182	467	195	550	411	358	319	520	410	372	280	242	526	265	480
6	261	233	249	506	394	254	187	168	429	166	498	331	297	286	469	353	312	247	227	476	229	466
5	187	160	232	384	274	184	172	158	385	145	452	259	226	270	429	309	243	230	210	426	207	448
4	166	143	222	313	204	168	165	138	344	136	420	238	207	256	392	275	221	219	185	379	188	423
3	154	133	212	276	168	158	160	124	276	131	391	215	194	245	333	229	210	211	158	328	176	392
2	142	125	194	229	133	152	155	116	219	126	359	201	184	236	288	189	201	209	156	291	168	368
1	125	108	186	222	132	138	153	118	210	128	337	184	179	234	281	190	199	209	161	281	168	361
Number of storeys: East facade																						
11	746	706	423	549	335	331	511	317	642	546	389	1095	1050	503	642	425	384	911	386	953	836	481
10	620	626	396	510	293	294	484	291	611	483	362	949	978	477	614	392	360	885	366	927	777	445
9	485	514	374	485	252	264	453	265	569	385	332	771	805	439	574	343	337	853	339	897	609	406
8	374	420	350	453	220	240	431	245	521	289	307	485	610	407	525	295	308	794	317	860	420	363
7	301	338	327	441	189	223	399	222	475	241	285	428	489	379	504	256	279	750	296	704	319	328
6	246	292	304	427	164	209	373	202	437	210	261	341	425	353	484	223	261	706	282	660	268	294
5	205	246	277	413	141	188	324	187	401	169	222	299	377	326	466	196	245	642	268	623	222	269
4	179	222	245	398	125	171	259	178	371	150	189	269	347	304	447	180	235	559	243	582	203	251
3	154	204	216	384	115	155	194	167	334	138	167	244	323	279	421	156	225	412	228	538	193	237
2	137	185	196	357	106	148	152	154	299	134	152	224	301	258	395	144	218	246	217	484	189	220
1	127	166	180	334	98	144	135	148	268	132	142	201	282	238	364	133	202	226	208	430	185	199

Number of storeys: South facade																						
11	363	385	348	347	237	253	365	194	349	208	231	636	703	642	606	331	412	672	318	629	254	349
10	312	373	334	338	214	222	350	173	338	185	208	572	687	625	595	305	377	646	288	607	237	326
9	255	355	317	324	185	180	321	148	330	158	179	493	659	606	588	278	327	597	242	593	217	304
8	212	310	302	314	158	146	273	125	320	134	152	442	595	586	580	254	258	526	199	574	170	281
7	174	243	283	292	133	119	212	104	300	113	128	381	516	561	554	233	225	444	182	545	153	256
6	141	195	264	258	114	100	170	89	277	97	105	334	442	533	502	212	200	379	163	513	137	229
5	120	164	246	217	99	85	143	78	254	83	92	298	398	505	444	193	181	332	140	479	126	210
4	105	143	221	179	88	74	124	70	228	74	81	262	359	462	396	179	156	293	130	441	109	194
3	96	127	191	150	81	68	113	66	197	68	75	219	334	415	365	169	116	274	121	394	100	179
2	90	117	164	135	77	64	104	63	168	65	72	199	308	382	343	162	108	262	119	360	99	172
1	85	108	142	123	72	60	95	60	145	61	68	193	283	362	324	150	96	240	103	336	90	168
Number of storeys: West facade																						
11	742	427	682	606	487	331	682	211	599	366	230	1168	844	1107	1085	891	420	1045	333	986	432	381
10	624	411	675	587	451	285	664	193	528	341	212	950	813	1094	1064	837	384	1019	308	891	395	358
9	488	388	663	566	422	246	630	174	427	308	191	765	784	1077	1042	785	338	993	277	711	353	326
8	377	362	629	537	381	214	608	157	344	253	170	558	739	1042	1020	731	290	951	243	563	322	290
7	301	334	591	500	327	183	574	142	291	216	149	497	674	994	993	622	252	890	220	481	294	266
6	246	305	554	471	265	157	542	131	251	195	133	380	625	947	956	522	222	831	195	403	258	244
5	205	261	505	445	207	138	501	117	210	172	121	329	563	834	908	361	201	748	176	354	227	229
4	177	218	446	419	181	122	451	107	197	154	113	295	478	692	855	326	185	636	166	317	208	214
3	153	175	393	384	154	109	389	103	181	140	108	270	388	571	808	230	164	522	152	289	198	193
2	135	147	347	346	131	100	338	100	164	129	104	247	296	461	708	206	152	419	146	256	183	182
1	126	133	323	280	122	95	317	96	153	121	99	224	277	440	592	200	132	395	140	234	165	174

Selected contexts   Solar irradiation level in kWh/(m^2 y)

■ Uniform and Random   ▒ Roof and Facade

Table A.21: Type T6 for North-South orientation in Florianopolis and Fortaleza.

T6_EW	Florianopolis											Fortaleza										
Surface	Urban context											Cases										
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Roof	1630	1363	1164	1498	1225	1014	1389	1001	1469	1286	1051	2398	2062	1726	2258	1704	1273	2215	1393	2064	1906	1438
Number of storeys: North facade																						
11	886	581	426	779	668	780	340	503	768	496	595	696	484	435	673	582	624	383	482	632	488	513
10	800	527	409	748	596	707	322	436	734	468	560	634	433	413	652	550	578	361	461	610	458	489
9	648	439	386	709	539	614	296	420	697	421	522	567	386	392	616	500	529	341	442	595	419	466
8	502	340	356	650	472	508	271	375	657	357	505	493	349	372	562	452	488	324	387	573	386	456
7	400	258	326	578	417	434	247	350	576	312	483	441	319	355	499	393	462	305	367	527	355	430
6	332	225	303	475	338	413	228	337	526	284	467	382	283	328	464	354	436	276	350	476	324	408
5	259	178	283	390	270	359	209	311	471	247	435	317	232	305	429	324	388	254	328	430	303	388
4	231	159	269	332	218	339	197	287	427	225	392	293	212	286	397	295	363	235	316	400	286	369
3	209	150	256	306	190	325	181	263	352	210	369	275	200	269	363	272	354	223	293	373	270	344
2	191	141	237	275	155	305	171	242	290	191	347	254	195	258	322	237	344	220	278	353	255	320
1	183	131	227	268	152	282	169	228	258	190	332	236	197	252	317	233	333	218	281	340	248	304
Number of storeys: East facade																						
11	744	641	251	428	252	248	528	252	449	479	235	1102	1037	338	537	334	272	839	301	582	762	314
10	597	519	222	361	224	224	495	229	430	418	213	932	918	306	485	305	252	822	278	565	713	288
9	439	382	197	304	188	207	461	212	409	347	191	730	696	269	404	259	230	799	252	548	643	260
8	327	284	174	252	159	193	430	196	390	278	174	409	468	234	323	203	210	648	226	524	427	231
7	251	227	152	225	132	180	393	180	360	212	157	356	336	205	287	173	191	530	202	464	304	208
6	193	191	135	206	111	169	341	165	338	172	140	250	259	180	259	147	176	485	181	440	223	171
5	159	153	122	190	95	160	292	150	302	133	120	213	213	159	235	130	162	428	164	420	176	144
4	135	138	112	173	84	152	239	138	277	120	109	192	193	141	219	117	154	368	151	394	155	133
3	118	122	106	158	77	145	195	127	242	111	101	176	180	131	184	107	146	312	139	361	144	126
2	104	111	99	141	72	138	162	118	208	106	98	161	171	124	166	99	140	248	133	317	138	116
1	97	102	98	134	68	134	140	114	179	103	92	151	165	119	157	94	135	209	131	281	134	110

Continuing Table A.22

Number of storeys: South facade																						
11	361	356	335	348	211	198	327	181	297	186	231	643	662	649	659	381	376	625	333	582	288	450
10	318	343	325	339	195	176	311	166	284	170	209	588	641	635	644	361	346	592	314	561	272	423
9	269	319	315	333	177	151	287	152	270	149	184	516	606	619	637	337	312	553	290	537	255	389
8	230	284	302	327	162	131	256	137	257	131	162	466	555	601	631	315	285	485	262	514	239	364
7	196	239	283	303	147	117	219	125	246	116	141	412	493	580	599	298	266	429	248	496	224	330
6	165	209	265	277	136	105	188	116	231	105	125	377	449	548	548	281	249	384	239	468	213	307
5	145	186	245	247	126	97	168	107	217	96	112	338	413	519	506	265	237	350	223	439	203	275
4	130	168	227	217	118	91	154	101	202	90	104	313	387	484	461	255	228	327	216	413	197	261
3	121	155	208	194	113	89	144	93	186	87	95	279	365	452	426	248	204	315	213	385	192	245
2	116	148	186	178	109	86	138	93	167	86	94	273	353	420	400	244	194	311	214	359	192	241
1	109	138	164	165	104	84	129	89	148	84	89	271	337	395	388	233	191	309	216	329	186	241
Number of storeys: West facade																						
11	741	356	504	759	490	230	506	193	606	284	200	1177	605	815	1206	716	278	819	281	943	368	335
10	598	338	464	751	463	203	463	176	536	260	181	915	588	804	1201	628	259	802	260	876	336	309
9	441	321	436	738	412	175	428	157	425	231	154	709	570	791	1200	592	223	782	239	676	297	265
8	328	301	407	706	370	152	397	141	326	200	130	457	547	707	1177	544	177	687	218	489	260	210
7	251	272	375	669	309	126	363	125	256	171	106	405	458	597	1147	466	157	570	201	391	227	179
6	193	246	329	627	247	108	315	109	208	146	92	273	409	559	1060	405	142	529	164	283	182	156
5	159	192	286	568	206	90	277	92	165	125	82	227	354	502	951	337	127	469	136	226	149	138
4	135	153	242	506	169	81	236	82	150	111	74	206	287	431	905	250	118	403	128	207	138	127
3	117	125	208	440	142	74	202	76	138	98	69	190	235	376	766	200	108	351	118	194	129	117
2	103	110	189	380	121	70	181	70	128	89	66	174	199	317	684	187	104	289	112	179	123	111
1	95	105	179	328	117	68	172	67	120	84	64	164	192	261	642	183	100	232	109	170	120	107

Selected contexts　　Solar irradiation level in kWh/(m^2 y)

■ Uniform and Random　　▨ Roof and Facade

Table A.22: Type T6 for East-West orientation in Florianopolis and Fortaleza.

Type T7: results in kWh/(m² y) for North-South (NS) and East-West (EW) orientations in Florianopolis and Fortaleza

T7_NS	**Florianopolis**											**Fortaleza**										
Surface	**Urban context**											**Urban context**										
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Roof	1630	1620	1585	1626	1581	1571	1610	1562	1623	1595	1580	2398	2391	2334	2394	2342	2287	2384	2302	2393	2340	2331
Number of storeys: North facade																						
13	923	926	804	978	907	948	778	842	915	788	897	731	746	657	798	743	756	643	669	766	639	740
12	882	909	756	967	894	932	726	807	905	741	886	702	727	639	788	731	739	622	642	758	622	732
11	839	879	641	949	877	902	604	760	886	624	872	670	698	620	771	711	711	598	612	748	602	720
10	785	837	591	930	855	863	552	713	871	571	859	638	666	603	753	687	676	580	584	737	584	708
9	731	796	558	907	824	823	517	654	857	536	847	606	633	579	728	661	644	553	559	723	560	696
8	640	745	481	871	783	770	440	527	838	453	830	582	604	561	702	634	614	539	539	702	538	686
7	540	702	452	838	748	728	409	497	822	423	818	566	578	551	678	606	593	529	518	683	527	670
6	513	651	442	808	708	677	399	467	794	412	807	548	559	528	654	580	572	506	501	666	504	657
5	469	523	433	772	668	555	383	387	775	399	792	519	540	520	632	556	551	497	488	652	495	638
4	379	486	426	729	631	519	374	357	748	384	775	504	516	492	610	536	533	465	473	639	465	619
3	366	448	406	657	566	476	353	346	711	357	760	480	499	460	593	518	514	431	456	624	429	602
2	357	371	367	556	477	401	316	341	640	319	746	462	488	431	574	499	505	397	435	608	398	585
1	355	356	362	544	469	386	311	340	615	312	730	443	476	419	551	481	500	385	410	593	389	566

Continuing Table A.23

Number of storeys: East facade																						
13	788	823	544	804	556	507	749	504	805	756	654	1140	1180	677	1170	865	630	1128	622	1171	1091	1021
12	755	805	531	772	525	491	732	492	796	739	614	1110	1158	664	1128	651	616	1116	608	1158	1070	897
11	691	786	517	721	486	475	701	478	785	720	569	1031	1136	648	1085	607	599	1101	592	1146	1042	874
10	631	759	498	678	464	457	678	460	762	698	541	996	1111	616	1016	583	565	1084	561	1135	1013	795
9	572	713	483	631	446	443	647	445	743	642	507	880	1058	575	923	562	522	1065	519	1124	956	612
8	520	655	453	598	423	416	622	416	731	586	474	818	1023	555	905	543	507	1042	503	1109	918	594
7	486	612	442	581	397	408	604	407	717	550	465	796	940	541	882	506	494	1016	492	1094	833	581
6	456	560	429	558	375	398	587	399	700	510	455	652	859	527	662	475	481	988	481	1076	758	564
5	410	519	418	528	332	390	560	386	678	476	440	541	836	511	642	458	468	961	467	1049	737	544
4	370	483	410	517	315	383	519	370	657	448	424	519	742	501	622	442	453	929	452	1029	643	502
3	349	437	397	507	296	369	487	348	631	418	400	498	581	486	605	424	437	877	437	1007	487	474
2	332	396	385	490	283	355	445	335	594	391	370	475	552	471	583	403	423	849	421	981	469	458
1	318	376	371	467	269	339	410	325	566	381	353	450	526	451	525	383	407	722	405	918	454	441
Number of storeys: South facade																						
13	392	421	412	413	328	353	415	312	415	308	326	676	752	740	726	557	627	740	547	748	509	554
12	370	411	406	406	316	340	405	298	409	295	314	647	739	734	718	543	604	728	523	742	489	540
11	345	401	399	398	301	323	393	281	402	282	298	617	727	726	709	528	569	717	499	733	463	525
10	323	392	400	390	286	295	379	262	403	261	283	590	715	730	702	511	545	701	478	740	445	508
9	299	381	392	379	271	273	364	247	396	247	269	567	701	723	691	495	516	676	457	725	428	496
8	279	364	384	367	258	253	343	232	387	234	254	531	676	715	676	480	487	642	435	713	413	485
7	264	342	373	352	247	237	322	218	381	223	242	514	649	705	659	457	468	617	420	705	404	474
6	252	321	362	338	236	224	302	208	371	213	231	500	626	693	644	444	451	592	410	687	394	459
5	237	299	347	320	224	209	280	196	354	202	219	488	601	677	626	429	429	567	398	665	376	441
4	224	278	327	301	213	195	261	185	336	191	207	475	581	656	613	420	411	541	390	637	365	432
3	211	261	307	282	201	184	244	175	315	180	196	460	552	627	596	413	402	520	380	611	358	428
2	198	243	285	260	188	172	222	164	292	169	185	441	538	608	583	396	394	504	371	593	341	411
1	174	223	261	238	171	157	199	150	265	154	170	426	517	580	562	383	380	487	361	567	329	392

Continuing Table A.23

Number of storeys: West facade																						
13	786	713	824	801	670	559	826	527	790	627	469	1214	1178	1260	1251	1160	839	1247	914	1226	949	824
12	752	692	817	786	644	534	814	484	768	594	438	1183	1158	1249	1240	1145	715	1235	795	1209	837	698
11	694	659	811	767	620	498	802	438	749	553	403	1032	1140	1240	1226	1124	662	1220	769	1191	812	647
10	633	628	805	751	597	469	790	407	729	526	380	992	1120	1230	1214	1096	640	1204	731	1169	775	630
9	576	604	781	729	578	444	773	375	687	483	365	880	1089	1214	1204	1047	614	1183	585	1042	631	613
8	525	581	760	703	550	421	752	340	633	449	347	821	1037	1195	1192	993	593	1156	562	964	609	594
7	490	561	737	680	526	397	731	326	599	438	328	793	1009	1170	1177	967	545	1127	542	882	592	545
6	459	545	724	654	503	375	720	312	560	423	315	709	979	1145	1160	878	501	1096	524	802	575	500
5	411	527	702	634	469	330	700	296	522	402	286	611	949	1123	1140	830	477	1072	504	782	552	476
4	372	506	672	613	426	312	672	276	487	379	275	589	920	1100	1117	746	450	1053	443	716	487	456
3	349	470	641	592	385	295	629	259	439	348	260	568	850	987	1091	687	426	951	411	609	445	441
2	332	438	603	570	353	282	592	236	408	311	249	543	821	944	1060	667	408	913	396	588	428	425
1	316	406	570	538	320	268	560	225	391	293	236	513	712	826	1028	590	391	799	380	570	411	408

Selected contexts — Solar irradiation level in kWh/(m^2 y)

■ Uniform and Random — □ Roof and Facade

Table A.23: Type T7 for North-South orientation in Florianopolis and Fortaleza.

T7_EW	**Florianopolis**											**Fortaleza**										
Surface	**Urban context**											**Urban context**										
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Roof	1630	1600	1506	1622	1555	1445	1614	1477	1612	1599	1531	2398	2349	2206	2391	2309	2101	2388	2158	2378	2342	2267
Number of storeys: North facade																						
13	929	854	828	959	923	954	779	821	959	850	851	739	711	675	795	761	766	654	681	798	684	724
12	893	829	803	943	910	936	750	794	952	827	839	715	686	660	785	750	751	633	659	793	668	715
11	859	793	716	919	878	913	655	764	939	739	824	689	662	644	770	727	734	614	637	778	649	701
10	812	759	675	894	840	879	606	736	919	694	805	661	639	631	755	703	704	598	617	757	634	686
9	775	723	656	865	803	848	583	708	894	673	785	632	605	616	722	668	683	576	601	742	618	673
8	706	681	600	834	765	810	524	608	874	616	758	612	580	602	702	650	662	560	583	723	607	661
7	613	649	571	804	734	783	490	578	855	588	741	597	552	584	686	633	646	541	569	707	591	647
6	586	619	557	773	701	752	475	566	834	575	725	579	537	571	660	601	621	531	561	694	582	636
5	550	517	538	743	664	658	452	519	812	550	710	550	523	565	641	582	608	524	551	683	571	624
4	477	488	523	716	632	628	438	491	793	525	696	539	513	554	626	563	595	518	540	666	554	607
3	455	470	506	665	580	610	422	483	767	497	680	522	504	533	610	544	581	495	530	646	521	589
2	436	416	479	585	488	556	397	476	736	466	660	505	496	509	598	529	570	470	518	627	498	569
1	427	398	471	577	476	539	392	470	718	455	648	493	484	498	579	509	558	459	509	596	488	547

Continuing Table A.24

Number of storeys: East facade																						
13	785	808	419	740	479	418	780	418	709	759	595	1145	1177	555	1082	809	537	1153	545	1079	1119	973
12	749	789	397	696	450	396	764	398	694	733	541	1111	1157	538	1054	567	521	1142	528	1070	1096	825
11	672	761	375	650	405	377	736	378	674	697	482	1016	1130	518	1017	518	503	1106	509	1057	1046	793
10	600	713	348	586	375	353	709	354	656	662	445	972	1082	468	925	494	453	1069	460	1012	998	706
9	531	641	330	521	352	336	680	337	633	623	406	834	997	412	810	470	399	1051	406	919	964	496
8	470	572	300	470	324	307	654	308	614	571	364	765	950	393	780	448	382	1028	388	905	928	474
7	429	526	289	443	298	298	629	297	603	522	346	739	854	375	743	392	369	1009	372	893	826	456
6	398	475	274	409	285	291	605	288	577	462	330	576	760	359	495	351	356	987	359	880	732	441
5	353	424	263	366	252	281	567	278	552	414	309	448	732	342	473	332	341	958	343	861	705	421
4	316	386	254	346	239	272	542	268	534	377	288	427	620	328	453	315	327	870	329	838	595	355
3	292	349	242	328	228	263	499	259	509	339	265	409	443	313	433	301	312	792	313	816	418	321
2	273	313	232	311	217	255	468	250	480	308	245	393	424	299	406	287	299	770	300	793	401	307
1	260	294	226	290	210	248	443	242	462	292	238	363	407	289	336	276	289	741	291	762	389	295
Number of storeys: South facade																						
13	388	418	401	421	329	322	407	302	397	298	338	682	758	744	759	590	599	734	550	733	519	601
12	371	410	396	415	318	309	398	291	391	288	326	659	741	736	753	570	575	722	533	719	498	589
11	351	402	389	407	308	295	389	276	382	276	312	635	723	726	745	551	557	710	516	703	485	575
10	332	390	389	401	294	281	373	266	376	266	301	612	703	731	739	540	533	689	497	698	470	562
9	314	374	382	393	283	265	360	255	369	254	288	592	681	724	727	529	506	662	479	688	451	549
8	296	362	375	384	271	250	345	244	359	244	276	561	667	716	714	518	474	635	462	678	428	537
7	284	344	366	373	260	240	329	235	349	236	266	549	648	711	700	509	461	617	453	670	419	529
6	272	327	357	363	253	231	317	229	341	228	256	531	630	702	688	502	451	603	444	661	413	514
5	261	311	343	347	244	218	302	220	328	219	243	521	609	687	670	494	436	588	429	646	404	502
4	250	298	327	328	234	204	288	213	312	209	229	509	595	670	657	485	425	556	423	625	396	497
3	237	283	311	310	225	194	275	203	298	201	216	492	582	641	633	480	417	546	419	610	393	491
2	225	265	293	290	213	184	261	194	280	187	204	489	571	624	618	475	411	539	412	595	389	486
1	199	242	268	265	196	169	239	179	254	170	190	478	556	600	593	462	397	524	397	571	381	457

Continuing Table A.24

Number of storeys: West facade																						
13	782	664	772	842	745	471	772	557	793	594	452	1219	1042	1233	1286	1077	771	1229	917	1230	933	780
12	746	646	758	836	719	443	756	502	775	542	421	1184	1029	1223	1282	1059	616	1218	779	1207	795	623
11	673	620	735	829	696	399	732	443	750	485	375	1000	1013	1163	1276	1037	556	1155	751	1175	767	564
10	600	600	715	824	666	371	710	407	717	448	347	950	965	1066	1275	1015	531	1056	705	1146	716	538
9	533	565	679	817	636	348	672	368	663	410	323	811	873	1049	1271	990	510	1036	527	1001	537	516
8	472	540	653	799	596	322	646	327	592	367	298	746	846	1026	1260	961	490	1013	505	928	514	495
7	431	522	628	776	573	297	618	310	539	348	274	720	826	1006	1243	908	417	991	489	832	496	422
6	399	492	602	761	536	285	592	293	489	330	262	616	805	985	1229	799	360	970	473	736	480	363
5	355	459	563	740	497	251	552	271	440	306	233	497	782	958	1207	763	344	943	456	707	463	346
4	318	439	541	717	470	237	533	245	401	284	217	477	761	883	1183	722	329	865	368	616	375	330
3	292	415	504	688	421	225	498	223	362	262	203	460	721	787	1149	695	313	771	325	487	328	316
2	273	386	479	657	388	215	473	202	331	238	192	444	705	769	1051	677	297	754	311	471	315	302
1	260	368	465	627	357	207	459	192	312	228	181	413	654	731	994	575	286	717	297	461	305	286

Selected contexts	Solar irradiation level in kWh/(m² y)
■ Uniform and Random	▨ Roof and Facade

Table A.24: Type T7 for East-West orientation in Florianopolis and Fortaleza.

Type T8: results in kWh/(m² y) for North-South (NS) and East-West (EW) orientations in Florianopolis and Fortaleza

T8_NS	Florianopolis											Fortaleza										
Surface	Urban context											Urban context										
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Roof	1630	1630	1630	1630	1629	1630	1630	1630	1629	1630	1630	2398	2398	2398	2398	2398	2398	2398	2398	2398	2398	2398
Number of storeys: North facade																						
17	912	1009	1011	1008	989	1012	1005	997	992	1004	983	717	822	819	819	801	826	815	807	811	816	796
16	861	1007	997	1013	979	1013	993	992	992	995	975	679	823	804	825	798	829	802	806	813	802	792
15	810	1002	982	1015	969	1011	976	979	988	982	966	645	819	786	828	793	830	778	796	812	785	788
14	756	997	967	1016	961	1010	958	963	981	962	959	607	815	770	831	786	826	763	777	809	763	781
13	688	985	939	1013	947	998	928	940	974	931	947	574	805	745	830	774	812	737	754	805	738	774
12	556	967	901	1004	933	986	886	912	965	893	932	548	787	714	824	770	798	704	731	801	707	771
11	499	941	858	992	913	967	837	876	951	847	913	513	758	682	815	751	773	667	698	792	672	759
10	422	912	820	976	893	944	791	835	940	807	899	484	727	654	798	733	750	636	665	783	644	749
9	364	884	762	958	869	915	723	787	925	747	879	460	703	632	778	713	724	611	632	772	621	737
8	342	840	645	932	841	875	599	744	912	628	861	429	666	611	756	684	692	586	598	758	600	722
7	323	794	609	902	814	833	561	696	895	590	846	410	633	592	731	655	657	567	571	741	581	709
6	306	739	553	862	773	780	504	575	869	530	829	375	595	573	697	623	620	544	546	711	559	689
5	242	687	486	822	720	728	436	516	847	462	805	325	567	562	670	594	595	533	526	684	543	669
4	230	593	475	784	677	632	424	485	827	448	787	306	545	541	642	561	570	516	507	667	521	644
3	221	507	466	746	641	553	409	398	798	433	770	297	530	533	617	541	552	505	494	654	513	622
2	214	478	460	684	579	530	396	383	766	421	756	292	506	508	598	520	533	476	478	637	482	604
1	212	403	430	582	481	459	364	378	750	389	741	287	491	463	577	499	523	428	470	617	436	584

Continuing Table A.25

Number of storeys: East facade																						
17	774	860	807	874	843	797	846	795	854	858	864	1124	1215	1168	1237	1199	1153	1201	1150	1212	1204	1223
16	722	847	759	869	815	746	839	744	846	850	854	1066	1207	1114	1232	1172	1094	1194	1091	1204	1196	1211
15	650	844	698	866	786	683	835	682	844	845	842	992	1203	1059	1228	1140	1035	1190	1032	1202	1190	1195
14	575	841	641	854	741	628	826	625	840	829	828	903	1199	964	1215	1091	942	1185	937	1198	1178	1176
13	509	835	588	844	676	574	818	573	835	815	802	789	1192	874	1201	1017	850	1178	847	1192	1163	1147
12	456	827	547	830	615	529	801	530	822	795	752	755	1181	850	1183	948	821	1165	819	1182	1140	1099
11	404	813	512	804	553	493	780	492	803	774	680	552	1155	615	1155	820	583	1149	580	1169	1114	1011
10	354	793	472	773	506	454	760	453	793	753	617	469	1133	581	1126	790	547	1136	545	1145	1087	968
9	323	767	457	715	470	437	740	438	780	729	567	445	1104	561	1052	604	527	1122	526	1133	1053	821
8	298	731	441	652	427	420	711	423	756	703	510	421	1064	541	1012	512	511	1105	508	1122	1018	794
7	274	676	421	601	401	402	677	405	741	652	474	390	1006	506	883	491	482	1082	476	1107	961	669
6	251	599	401	544	374	383	642	386	721	576	435	331	945	453	830	471	427	1042	423	1083	898	517
5	220	539	373	517	352	357	618	357	695	519	412	313	819	438	749	448	413	1004	409	1058	774	497
4	209	479	358	485	322	350	579	348	674	460	398	299	758	425	559	389	402	977	396	1036	716	481
3	198	439	347	456	285	341	544	340	650	429	384	287	726	412	539	370	388	946	383	1012	692	464
2	188	402	338	443	269	334	504	331	615	401	357	274	492	400	519	354	376	894	372	959	466	410
1	179	353	324	422	255	310	451	321	565	366	322	263	455	382	498	336	360	842	359	897	431	383
Number of storeys: South facade																						
17	381	412	412	427	415	403	414	410	411	408	418	661	749	743	750	723	732	750	737	744	709	722
16	353	408	408	422	398	394	410	395	406	390	402	626	745	739	745	700	722	746	716	739	684	700
15	327	414	414	425	384	389	414	386	412	369	385	592	754	749	750	676	718	754	700	748	652	676
14	300	410	410	421	361	376	411	366	408	339	362	563	751	745	746	647	706	750	675	745	622	649
13	276	413	412	423	339	365	414	343	412	314	338	529	754	749	752	620	686	754	643	751	582	620
12	255	409	409	418	318	352	410	316	408	291	316	496	751	745	748	594	661	749	610	747	545	593
11	235	406	406	415	296	335	407	284	407	268	293	470	748	746	744	571	636	746	565	749	514	567
10	218	396	401	408	277	319	398	261	402	251	275	453	735	742	737	551	613	733	530	745	494	547
9	203	386	398	399	261	298	386	241	399	235	259	429	722	742	729	534	578	718	501	743	468	530
8	190	370	390	389	246	276	370	224	393	221	245	407	703	735	719	516	546	697	478	738	447	514

Continuing Table A.25

7	173	351	384	375	233	247	348	207	386	204	231	382	676	729	703	500	516	669	456	730	431	501
6	160	327	372	356	220	220	322	192	374	190	216	363	635	715	680	476	483	623	435	705	413	488
5	151	299	358	339	210	202	295	179	360	180	203	345	595	699	658	455	454	590	417	680	396	479
4	143	276	342	320	201	187	272	169	343	173	193	338	567	680	637	446	434	566	407	656	388	456
3	137	255	319	298	191	175	252	161	322	166	185	335	546	657	621	431	411	544	395	628	369	442
2	131	235	296	276	182	165	234	153	299	158	176	319	528	626	599	424	396	524	390	600	359	436
1	120	210	267	249	165	150	209	141	269	144	162	309	504	593	572	414	382	503	380	574	349	429
Number of storeys: West facade																						
17	771	834	852	850	833	835	855	839	861	849	826	1199	1273	1290	1284	1269	1258	1285	1268	1296	1270	1257
16	718	813	841	847	823	819	842	819	858	832	793	1115	1260	1285	1280	1261	1238	1279	1247	1293	1250	1228
15	651	805	840	846	813	787	839	800	856	817	765	980	1253	1285	1280	1253	1206	1278	1225	1291	1232	1200
14	576	794	838	844	791	739	838	776	851	801	715	898	1241	1285	1278	1236	1138	1277	1201	1283	1212	1132
13	510	782	835	840	770	677	835	737	843	775	646	784	1230	1283	1276	1221	993	1273	1165	1274	1183	984
12	460	766	828	832	749	617	828	678	828	728	578	747	1218	1276	1273	1207	919	1267	1114	1259	1128	914
11	407	739	822	825	724	561	820	605	806	660	510	596	1192	1259	1267	1190	799	1248	939	1237	952	795
10	355	713	809	814	694	512	804	525	783	596	451	530	1137	1245	1263	1173	770	1230	884	1211	906	764
9	325	687	797	799	661	476	790	470	758	550	409	505	1109	1233	1251	1150	652	1215	741	1185	770	644
8	299	649	786	785	632	436	777	411	729	497	367	480	1091	1218	1244	1101	569	1198	709	1156	741	561
7	275	621	767	766	607	406	753	371	685	461	339	443	1041	1200	1235	1020	545	1176	630	1028	662	541
6	250	584	725	735	561	381	713	330	615	417	321	351	1006	1157	1217	977	521	1126	506	926	539	522
5	221	555	701	698	534	358	693	304	561	389	304	334	970	1101	1193	915	496	1066	485	799	519	499
4	209	530	669	672	494	327	664	287	511	371	280	319	939	1077	1172	850	410	1043	466	742	500	410
3	198	502	639	646	430	290	636	269	476	352	250	307	907	1035	1145	772	390	1006	449	717	483	388
2	188	474	610	621	386	273	605	246	439	324	237	294	827	931	1120	682	368	904	376	576	403	371
1	178	428	570	594	349	256	562	221	397	288	221	283	774	889	1090	662	349	867	345	534	367	357

Selected contexts	Solar irradiation level in kWh/(m^2 y)
■ Uniform and Random	▨ Roof and Facade

Table A.25: Type T8 for North-South orientation in Florianopolis and Fortaleza.

T8_EW	**Florianopolis**											**Fortaleza**										
Surface	**Urban context**											**Urban context**										
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Roof	1630	1630	1630	1630	1630	1630	1630	1630	1630	1630	1630	2398	2398	2398	2398	2398	2398	2398	2398	2398	2398	2398
Number of storeys: North facade																						
17	913	1007	1011	1020	1008	1016	1006	1000	1007	1007	986	719	825	826	833	825	834	821	817	827	820	802
16	866	997	998	1018	1008	1015	990	989	1004	999	977	684	822	814	834	825	833	806	808	827	808	796
15	820	991	982	1024	1003	1014	971	978	1002	983	967	652	816	795	841	819	833	786	801	827	787	792
14	771	983	963	1018	1000	1008	950	954	999	960	955	613	810	774	835	817	826	765	776	827	769	782
13	711	967	938	1015	990	1003	925	933	994	942	942	582	796	753	835	810	819	741	758	823	750	776
12	587	947	907	1001	974	991	886	904	980	909	920	559	773	726	826	797	803	709	735	815	723	769
11	531	914	866	992	956	971	836	869	968	870	900	524	742	693	819	784	781	672	702	807	692	753
10	466	880	836	967	934	948	793	831	958	841	882	490	709	667	799	764	757	645	673	798	668	738
9	406	847	789	946	906	924	737	790	947	796	864	469	685	645	781	739	735	619	645	788	645	727
8	382	807	680	917	873	890	623	750	933	683	846	447	654	624	757	714	708	597	615	772	621	712
7	357	761	646	887	833	851	585	715	914	650	827	431	624	609	736	684	675	581	593	752	604	699
6	333	712	605	847	787	806	539	611	884	605	803	401	590	595	701	649	646	561	572	719	588	678
5	275	671	548	808	741	762	476	552	857	542	773	353	567	583	674	622	623	547	551	693	571	660
4	260	588	534	769	698	680	461	533	834	524	751	337	543	570	646	591	598	533	537	680	563	639
3	250	508	524	735	661	609	446	461	808	502	731	326	524	559	627	570	581	522	525	668	556	617
2	242	483	517	684	607	590	435	454	787	488	712	318	506	536	610	550	566	501	517	648	528	599
1	241	423	495	591	510	519	412	451	768	458	689	311	489	492	589	529	554	456	509	625	485	578

Continuing Table A.26

Number of storeys: East facade																						
17	774	855	795	873	847	791	844	789	847	861	860	1129	1214	1158	1235	1199	1149	1196	1145	1204	1210	1217
16	718	848	739	867	827	732	839	730	832	854	848	1066	1209	1095	1228	1175	1082	1192	1078	1190	1203	1202
15	640	845	669	861	790	660	836	659	826	848	836	985	1207	1031	1222	1139	1015	1190	1013	1185	1197	1186
14	560	841	603	837	734	597	833	596	820	837	823	890	1202	926	1200	1081	911	1187	908	1179	1188	1168
13	488	834	540	822	659	535	826	534	809	825	795	772	1195	827	1181	999	812	1182	810	1171	1176	1138
12	433	824	489	801	587	484	805	483	787	798	736	736	1182	797	1153	921	783	1166	780	1143	1149	1083
11	380	802	446	772	515	442	789	441	769	774	654	520	1164	545	1121	783	530	1154	528	1111	1121	985
10	330	784	401	732	463	397	775	396	745	749	581	433	1142	503	1081	752	489	1144	488	1098	1088	934
9	298	756	376	680	424	378	758	376	731	713	522	409	1114	481	1005	559	470	1130	467	1086	1055	774
8	271	710	357	606	378	360	728	359	712	675	461	388	1071	461	963	460	451	1107	450	1073	1017	743
7	247	652	335	546	347	340	700	340	687	633	420	357	1001	426	820	437	415	1059	415	1056	952	609
6	222	579	312	480	323	320	658	319	660	558	374	291	930	365	760	416	354	1025	355	1028	897	450
5	194	514	285	442	301	294	628	291	642	494	346	273	796	351	672	389	341	998	341	931	762	432
4	183	447	276	401	272	287	595	282	601	434	326	258	730	337	473	322	330	972	328	898	695	416
3	176	407	265	371	241	280	559	276	582	394	310	247	700	323	455	307	319	942	318	879	666	400
2	167	372	252	349	230	273	515	269	551	358	288	238	462	310	438	297	309	904	308	859	429	340
1	157	324	246	330	220	264	478	265	515	319	266	231	427	299	423	284	299	833	297	835	397	311
Number of storeys: South facade																						
17	379	428	419	428	419	401	422	411	420	406	418	663	771	756	758	730	731	762	737	760	709	729
16	353	425	415	425	403	392	417	397	415	389	405	630	768	753	755	707	720	756	718	754	685	709
15	329	428	420	428	391	384	422	386	421	369	393	600	775	761	763	688	711	760	701	762	654	690
14	303	424	415	425	373	370	417	367	416	343	375	571	771	756	760	663	699	755	676	756	625	666
13	282	427	414	428	350	357	417	346	416	321	355	532	773	756	766	636	671	758	642	758	583	641
12	262	424	409	424	332	344	411	321	410	301	336	504	770	752	762	614	647	751	610	753	550	617
11	243	420	406	419	313	328	409	294	405	282	316	482	766	751	758	592	626	747	567	749	526	592
10	227	410	399	413	297	313	399	272	397	266	299	463	755	745	753	573	605	734	536	741	507	574
9	213	399	397	409	282	294	388	254	391	251	286	437	739	746	749	555	567	721	509	735	477	560
8	200	386	390	399	270	276	372	240	382	238	270	414	715	737	740	534	539	701	489	722	457	544

Continuing Table A.26

7	188	372	383	387	258	254	351	227	372	226	256	398	688	730	726	516	513	668	469	707	443	532
6	174	350	372	372	244	232	329	214	362	214	242	384	654	717	705	497	485	622	447	688	428	518
5	163	325	360	358	232	217	308	203	350	206	229	365	627	703	684	484	456	599	431	670	409	507
4	155	303	341	338	221	204	288	195	333	198	219	358	605	688	661	477	438	579	423	651	399	482
3	149	283	319	316	212	192	270	186	315	191	208	354	585	667	645	470	418	558	410	628	387	475
2	143	265	299	293	201	179	254	178	293	180	195	345	571	635	618	463	406	535	404	603	380	472
1	131	240	269	262	183	162	230	164	262	163	178	335	549	601	589	451	394	518	395	578	371	463
Number of storeys: West facade																						
17	772	827	846	842	847	834	848	840	861	847	822	1204	1264	1281	1270	1277	1259	1280	1273	1296	1274	1257
16	715	807	838	841	842	819	840	825	857	833	788	1114	1250	1278	1270	1272	1241	1275	1256	1291	1258	1224
15	641	798	836	842	838	783	837	809	855	820	761	966	1242	1277	1272	1268	1207	1273	1236	1289	1239	1196
14	561	787	834	843	820	727	834	790	852	805	710	879	1231	1276	1275	1254	1129	1271	1215	1283	1219	1126
13	490	772	830	843	810	657	830	755	844	777	636	758	1219	1273	1276	1243	971	1267	1182	1275	1189	966
12	435	748	812	840	798	586	812	695	830	720	561	723	1168	1256	1276	1231	895	1249	1124	1261	1131	887
11	383	720	790	836	780	519	790	611	809	642	487	558	1086	1243	1274	1215	765	1236	932	1237	941	756
10	332	692	778	831	752	465	776	530	777	570	429	485	1068	1232	1272	1181	733	1223	877	1205	888	724
9	299	665	761	823	729	425	756	470	751	512	385	462	1047	1221	1269	1070	603	1209	726	1167	738	594
8	272	632	738	814	695	379	730	407	723	453	338	441	1023	1198	1264	1037	514	1183	697	1127	709	507
7	247	602	718	803	666	349	707	366	666	415	309	408	998	1107	1256	1004	490	1088	610	1009	620	486
6	221	567	686	778	617	324	673	318	586	369	284	312	957	1052	1240	967	465	1032	477	901	484	463
5	194	541	654	749	577	303	641	289	520	338	266	293	875	1023	1219	923	437	1003	457	768	466	435
4	184	496	610	724	524	276	598	269	459	316	243	277	829	995	1197	872	343	977	441	710	451	340
3	176	473	579	699	478	245	569	250	420	297	217	266	804	966	1172	787	326	952	424	682	435	325
2	167	442	546	673	422	230	537	226	388	273	205	258	751	904	1151	697	316	884	342	524	353	314
1	156	404	508	640	381	218	501	201	349	246	189	252	732	854	1109	677	307	835	312	480	320	304

Selected contexts	Solar irradiation level in kWh/(m² y)
■ Uniform and Random	▨ Roof and Facade

Table A.26: Type T8 for East-West orientation in Florianopolis and Fortaleza.

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List of Nomenclature/Symbol

Nomenclature

ABNT	Associação Brasileira de Normas Técnicas *(Brazilian Standardization Ogranization)*
ACH	Air Change per Hour
AHS	Ângulo Horizontal de Sombreamento *(Horizontal Shades Angle)*
ANEEL	Agência Nacional de Energia Elétrica *(Brazilian National Electric Energy Organization)*
AVS	Ângulo Vertical de Sombreamento *(Vertical Shades Angle)*
BAPV	Building-Added / Attached Photovoltaic
BIPV	Building-Integrated Photovoltaic
BLAST	Basic Local Alignment Search Tool
CAD	Computer Aided Design
CCA	Concrete Slab
CECAS	Centro de Estudos do Clima e Ambientes Sustentáveis *(Study Center for Sustainable Climates and Ambients)*
CHPPS	Combined Heat and Power Plants
COP	Coefficient of Performance
CSI	California Solar Initiative
CSV	Comma Separated Values
DOE	Department of Energy
DSSC	Dye-Sensitized Solar Cells
DA	Daylight Autonomy
ECBCS	Energy Conservation in Buildings and Community Systems
ENCE	Etiqueta Nacional de Conservação de Energia *(Brazilian National Energy Saving Label)*
ENEV	Energieeinsparverordnung *(German Regulation for the Economic Use of Energy)*
EPBD	Energy Performance of Buildings Directive
EPFL	École Polytechnique Fédéral de Lausanne
EU	European Union
FA	Fator Altura *(Height Factor)*
FF	Fator de Forma *(Form Factor)*
FORTRAN	Programming Language
GI	Grid Interaction

GIZ	Deutsche Gesselschaft für Internationale Zusammenarbeit *(German Association for International Cooperation)*
HVAC	Heating, Ventilation, and Air conditioning
IEA	International Energy Agency
INMETRO	Instituto Nacional de Metrologia, Qualidade e Tecnologia *(Brazilian National Institute of Metrology, Quality and Technology)*
INP	Installed Nominal Power
KfW	Kreditanstalt für Wiederaufbau *(German development bank)*
KIT	Karlsruher Institut für Technologie *(Karlsruhe Institute of Technology)*
LBNL	Lawrence Berkeley National Laboratory
LEED	Leadership in Energy and Environmental Design
LIPV	Landscape Integrated Photovoltaic
LM	Load Matching
LMGI	Load Matching and Grid Interaction
m-SI	Monocrystalline silicon
NBR	Norma Brasileira *(Brazilian Norm)*
NOCT	Nominal Operating Cell Temperature
OPV	Organic Photovoltaic
PBE	Programa Brasileiro de Etiquetagem *(Brazilian Labeling Program)*
PCE	Power Conversion Efficiency
PROCEL	Programa Nacional de Conservação de Energia Elétrica *(Brazil's National Electricity Conservation Program)*
PV	Photovoltaic
RAC	Requisitos de Avaliação da Conformidade para Eficiência Energética de Edificações *(Requirements for the Assessment of the Conformity of the Energy Efficiency of Buildings)*
RTQ-C	Requisitos Técnicos da Qualidade para o Nível de Eficiência Energética em Edifícios Comerciais, de Serviços e Públicos *(Technical Regulation for the Quality of Commercial, Services and Public Buildings)*
RTQ-R	Regulamento Técnico da Qualidade para o Nível de Eficiência Energética em Edifícios Residenciais *(Technical Regulation for the Quality of Residential Buildings)*
SCH	Solar Heating and Cooling Program
SHGC	Solar Heat Gain Coefficient
STC	Standard Test Conditions
STPV	Semi-transparent photovoltaic
SWERA	Solar and Wind Resource Assessment
TMY	Test Meteorological Year
UDI	Useful Daylight Illuminance

UFPA	Universidade Federal do Pará *(Federal Universtiy of Para)*
UFRGS	Universidade Federal do Rio Grande do Sul *(Federal University of Rio Grande do Sul)*
UFSC	Universidade Federal de Santa Catarina *(Federal University of Santa Catarina)*
U.S.	United States
USP	Universidade de São Paulo *(University of Sao Paulo)*
VT	Visible Transmittance
WWR	Window to Wall Ratio
ZEB	Zero Energy Building

Symbol

A	Absorptance
β	Glass reflection
ε	Glass absorption
ΔT	Difference of temperature
η_{PV}	Solar cell efficiency
ϑ_{G}	Outside glass temperature
ϑ_{PV}	Solar cell temperature
ϑ_{S}	Outside glass surface temperature
λ	Thermal conductivity
P	Density
τ	Transmittance
cp	Specific heat coefficient
Cth	Thermal mass
E	Electric energy
E_{daily}	Daily solar irradiation
E_{STC}	Solar irradiation for standard test conditions
EAP	Estimate of annual produced
EFF_{NOCT}	Corrected efficiency
EFF_{STC}	Normalized efficiency
f	Index
GP	Grid price
ICP	Installed cost of the project
K	Temperature coefficient
k_{eff}	System performance correction factor
k_{tmp}	Temperature coefficient
n	Number of modules
P_{ins}	Installed power
P_{nom}	Nominal power
$\dot{q}$	Heat flux
$\dot{q}_{\mathrm{abs}}$	Absorbed heat flux
$\dot{q}_{\mathrm{cond}}$	Conductive heat flux
$\dot{q}_{\mathrm{conv}}$	Convective heat flux
$\dot{q}_{el}$	Generated electricity

$\dot{q}_{\mathrm{rad}}$	Radiative heat flux
$\dot{q}_{sol}$	Solar radiation
R	Thermal resistance
T	Time interval
T_P	Payback period
U	Thermal transmittance
W_{el}	Generated electricity

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