**A dissertation submitted to the Department of Environmental Sciences and Policy of Central European University in part fulfilment of the Degree of Doctor of Philosophy**

# NET-ZERO ENERGY BUILDINGS: GLOBAL AND REGIONAL PERSPECTIVES

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Net zero-energy building (NZEB) is usually understood as a highly energy efficient building, in which the remaining (low) energy demand is supplied with renewable energy.

Net-zero energy/emission mandates have been mushrooming worldwide, while the expert community remains divided or at least cautious with regard to the feasibility or environmental desirability of forcing such construction/retrofit in certain cases.

The aim of this research is to contribute to the debate around the NZEB concept from global and regional perspectives through analyzing the role of solar energy produced on site together with energy efficiency measures in meeting building energy demand. In order to achieve this goal a special model – BISE model – has been developed, which allows for estimating solar thermal and electric energy output from advanced building-integrated hybrid technologies taking into account various geographical, architectural, morphological and climatic parameters.

This model is based on a novel methodology combining bottom-up energy modelling with geospatial analysis and outstanding visualisation techniques. A comprehensive bottom-up energy model, developed by Centre for Climate Change and Sustainable Energy Policy, has been used in order to estimate global and regional building energy demand with certain data inputs from BUENAS model (particularly for energy use by appliances and lighting).

Combining the results on energy demand and potential solar energy supply provides a valuable scientific insight on the locations and building types where it is feasible to achieve the net-zero level of energy performance through application of solar technologies. The results show that realization of technical potential for state-of-the-art solar energy technologies in the building sector together with energy efficiency improvement will significantly reduce global and regional energy use and will allow for achieving net-zero energy goals in a number of locations and building types.

Energy efficiency plays a crucial role for NZEBs, as moderately efficient buildings have much less chances to become NZE, at least in developed countries. High-rise buildings are unlikely to achieve NZE target relying solely on solar energy and will require supplementary sources of energy supply. Low-rise buildings have a greater potential for NZE balance due to larger roof area available for solar technologies in relation to floor area. In some locations short-term solar energy storage applied in low- and medium-rise buildings can help them to become not only NZE, but also energy self-sufficient.

Climate conditions should be taken into account when choosing solar technologies. In cooling-dominated climates it is more reasonable to optimize the system in a way it maximizes solar electricity output, while excess solar heat can be used, for example, for solar cooling. Highly efficient appliances can increase chances for sufficient solar supply in residential buildings, while in commercial sector efficiency of lighting can make the difference.

Results also show the possibility for 'solar leapfrogging' in a number of developing countries. These countries usually have abundant solar resources and realization of this potential on building site can significantly reduce or even eliminate the need for fossil fuels.

It is the first time that such a detailed modelling exercise has been done on the global scale. This piece of work presents a high value for policy-makers in the fields related to the climate change mitigation, sustainable building design and solar energy technologies development.

**Keywords:** net-zero energy buildings, solar energy, energy efficiency, modeling, scenario analysis, hybrid PV/T technologies

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# I CHAPTER. INTRODUCTION

## I.1 The role of Net-Zero Energy Buildings for a sustainable future

Energy use in the building sector is increasing rapidly both on the global and regional levels. The most recent and comprehensive forecast for global thermal energy use in the building sector, conducted by the Centre for Climate Change and Sustainable Energy Policy (3CSEP) under the umbrella of Global Energy Assessment (GEA), has shown that without active and ambitious proliferation of existing energy efficiency best-practices in buildings, global energy use for space heating and cooling will increase by 32.5% by 2050 in during buildings' construction and renovation worldwide will almost halve the global thermal energy use in the building sector (Urge-Vorsatz, et al. 2012).

This analytical work had been extended under initiative of Global Building Performance Network (GBPN) and resulted in an even more comprehensive model with a more thorough building typology, updated data, three revised scenarios (Deep, Moderate and Frozen Efficiency), as well as enlarged number of analyzed end-uses (see Section V.1.1). The results of this study are similar to the ones presented in GEA: energy efficiency can help to reduce total thermal energy use in buildings (space heating, space cooling and water heating) by approximately one third (29%) by 2050 (i.e. under Deep scenario), while moderate efforts will lead to 48% increase (Moderate scenario), and the absence of action (Frrozen scenario), – to 111% increase within this timeframe (Urge-Vorsatz, Petrichenko, et al. 2012).

These analyses, however, focused on energy efficiency measures and did not take into account utilization of renewable energy sources (RES) in buildings, which could lead to even more considerable fossil fuel energy use and related greenhouse gas (GHG) emissions reduction.

Usage of fossil fuels in buildings causes depletion of energy resources and deterioration of environment (Zhu et al. 2009). Therefore, it is necessary to combine energy efficiency improvement of buildings with introduction of renewable energy applications. If a building's energy demand is covered by renewable energy production, it is usually considered as a net zero energy building (Zhu et al. 2009). However, in reality the concept of net zero energy building (NZEB) is much more complex, has different definitions and a rather long history (which is discussed in more detail in Chapter II).

**A net zero-energy building (NZEB)** is a residential or commercial building with greatly reduced energy needs through efficiency gains such that the balance of energy needs can be supplied with renewable technologies". However, the authors state that a net-zero energy building "can be defined in several ways, depending on the boundary and the metric" (Torcellini, Pless, and Deru, 2006)

The concept of NZEBs has been proliferating worldwide through policy agendas during last decade. For example, a recent recast of EU Directive on Energy Performance of Buildings (EPBD) has stated that all new buildings in the member states should be nearly zero energy buildings by 2020 (The European Parliament 2010). Under EPBD framework a number of member states have already introduced the targets for achieving NZE status in their building sectors.

France is aiming to construct only energy-positive[1] buildings by 2020. Germany's goal is to have buildings operating without fossil fuels by 2020. Hungary has set a goal for new buildings to be zero-emissions by 2020 and for large investments already in 2012. According to the Netherlands' plans, new buildings will be energy-neutral by 2020. UK has even more ambitious target – to

[1] Energy-positive buildings are the buildings, in which renewable energy generation exceeds energy demand

provide zero-carbon buildings already by 2016 (European Commission 2009). World Business Council for Sustainable Development has based the transformation of the building sector in the Vision 2050 on the moving to net-zero energy buildings by 2050 worldwide (WBCSD 2010).

Although the concept of net-zero energy buildings has become widely used in policy-making, scientific research in this field is still limited. Both theoretical and methodological aspects of this and related concepts are under-investigated. The targets outlined above have been set without a complete understanding of different aspects of NZEBs. At the moment there is neither a single definition of a NZEB nor a unified methodology for calculating energy balance in order to determine whether NZE goal is achieved or not. Moreover, there are only few examples with energy performance measured over several years. It is not clear at the moment whether such buildings can be constructed in all regions; how they perform in different climate zones and what technologies are needed to achieve NZE status under different conditions. There are no answers for these questions at the moment.

At the same time NZEBs are vital for climate change mitigation. Construction of such buildings is crucial for the future of our planet's climate and sustainable development. If most buildings' energy needs can be met by renewable energy it will considerably decrease global energy demand and related GHG emissions.

Therefore, it is very important to investigate how far can buildings take us on the way to net-zero energy future. Where it is feasible to construct such buildings as a sufficient amount of renewable energy resources is available and where it is necessary to look for the alternatives. This PhD research is devoted to answer these crucial questions. The main contribution of the research is to provide the base for a better understanding of NZEB concept, present the analysis of the feasibility of such buildings on the global and regional scales and help to clarify the role of NZEBs in tackling the climate change challenge.

## I.2 Research aim, goal, questions, objectives

In practice net zero energy/emission mandates have been mushrooming worldwide during the last decade, while the expert community remains divided or at least cautious with regard the feasibility or environmental desirability of forcing such construction/retrofit in certain cases. ***The aim*** of this research is to contribute to the debate from a global and regional perspective through analysing the role of solar supplied energy efficient buildings in reducing global and regional energy demand and mitigating climate change challenge.

**Research aim** is to analyze the role of solar supplied energy efficient buildings in mitigating climate change challenge

This aim requires achieving a more specific ***research goal***: to estimate maximum possible technical potential for covering global and regional building energy consumption with solar energy produced with building-integrated state-of-the-art solar energy technologies.

**Research goal** is to estimate maximum possible technical potential of building-integrated solar technologies in meeting building energy needs in different regions and worldwide

Achieving the outlined aim and goal requires answering the following ***research questions***:

- In what regions and climate zones are NZEBs technically feasible, according to the local climatic conditions and availability of natural resources?
- How does the potential for solar NZEBs vary across different building types?

- How much building energy needs can be met by 2050 with solar energy produced by building-integrated solar energy technologies?
- What are the implications of the research for policy development to drive the building sector toward net-zero energy goals?

In order to answer these research questions several ***objectives*** need to be accomplished. Firstly, a global and regional model for estimating and projecting energy demand and $CO_2$ emissions from buildings has to be developed. Secondly, the model for computing potential building-integrated solar energy supply has to be elaborated. Thirdly, the outputs of both models need to be analysed in order to understand how much of building energy demand can be met by solar energy supply. Finally, the results have to be interpreted with the purpose to assess the technical potential for solar-supplied NZEBs under different conditions.

**Research objectives:**

1) To estimate global and regional building energy use for each end-use
2) To estimate global and regional potential building-integrated solar energy supply
3) To evaluate how much of estimated building energy use can be met by potential solar energy supply
4) To make conclusions regarding technical potential for NZEBs for different regions, climate zones, building types.



The research work described in this dissertation in pursue of the outlined objectives is based on a novel methodology combining energy modelling and geospatial analysis. A comprehensive bottom-up energy model is used to estimate global and regional building energy demand. In order to evaluate what share of this demand can be met by building-integrated solar energy production, various geographical, architectural, morphological and climatic parameters have been analysed by means of rigorous geospatial analysis. Combining the results on energy demand and potential solar energy supply provides a valuable insight on the locations and building types where it is feasible to achieve a net zero level of energy performance.

It is the first time that such a detailed modelling exercise has been done on the global scale. The results show how much of global building energy use can be covered through the combination of ambitious energy efficiency improvements together with on-site generated solar energy through a hypothetical realisation of maximum achievable technical potential worldwide, and where it is not feasible at the moment to aim at achieving zero-net energy level in buildings solely with solar energy due to limited specific availability of solar resources in some case and other constrains.

## I.3 Contribution to the field of knowledge

As the result of the research work presented in this dissertation a novel methodology for estimating solar energy potential in buildings and evaluation of technical feasibility of net-zero energy buildings in different locations of the world has been elaborated. It is based on the combination of energy modelling and a comprehensive GIS analysis. For the first time this kind of analysis has been done on the global scale with the possibility to present the results for certain regions as well.

This piece of work presents a high value for policy-makers in the fields related to the climate change mitigation, sustainable building design and solar energy technologies development. First of all, the PhD dissertation presents a comprehensive analysis of a net-zero energy buildings concept, including the discussion of appropriate definitions, technological best-practices and existing case studies. These aspects are very important for modern policy-making, as at the moment a great interest in this concept is accompanied by the lack of the unified terminology and methodological framework. This work is devoted to help policy-makers and experts to view different aspects of net zero energy buildings and agree on key issues.

Secondly, reduction of building energy use through energy efficiency measures and building-integrated solar energy technologies has been estimated. The results demonstrate a key role of the building sector in climate change mitigation, designing necessary strategies and policy instruments.

Finally, the technical feasibility of net-zero energy buildings has been evaluated for different locations. This provides the insight for policy-makers on the climatic conditions, regions and building types for which the implementation of net-zero energy buildings has a practical potential. Recommendations for the utilisation of various definitions of NZEBs are also provided.

## I.4 Structure of the manuscript

The manuscript is structured around nine chapters. The current Chapter I introduces the concept of net-zero energy buildings and discusses its importance for climate change mitigation and future sustainable development. It justifies the importance of this research, presents its contribution to the field of knowledge and introduces research aim, goal, questions and objectives. Chapter II discusses the concept of net-zero energy buildings in more detail: it presents the review of different definitions, related technologies and measures and provides a number of NZEB case studies. Chapter III focuses on different types of solar energy technologies and their application in buildings. Special attention is paid to hybrid solar PV/T systems as a central technology analyzed in this study.

Chapter IV presents theoretical framework for this study, which is based on two pillars: energy modeling and GIS analysis. Chapter V overviews the design and methodology for this research and provides the details on the structure, calculation procedures and input data used in the model developed during this PhD work.

Chapter 0 describes different approaches for modeling roof area available for solar systems installations and introduces the methodology used in this dissertation. Chapter 0 outlines the main assumptions used for modeling exercise of this dissertation, while Chapter VIII reports its results by grouping then into ten key messages.

Finally, Chapter IX summarizes key results and draws conclusions for the dissertation, discusses the implications of the research and outlines possible directions for the further research development.

# II CHAPTER. NET-ZERO ENERGY BUILDINGS CONCEPT

As it was pointed out above in order to minimize the impact of a building on environment, it is necessary to combine energy efficiency improvement with utilization of renewable energy. If a building's energy demand is covered by renewable energy production, it is usually considered as a net zero energy building (Zhu et al. 2009). However, in reality the concept of net zero energy building (NZEB) is much more complex, has different definitions and a rather long history.

The net zero energy is considered as the difference between energy consumption and energy production in a building system. However, the utilization of this concept in the building environment is rather new. It has been borrowed from ecological economy where it is a much wider term.

For example, Podolinsky (2004) can be considered as on of the first "net energy study" in history focused on solar energy, as he studied the relationships between "accumulated solar energy" of human activity and economic production (Hernandez and Kenny 2010). Another early net energy analysis was conducted by the "Technical Alliance"[2] in the United States covering different industries and the energy process of a capitalism system, which set the ground for energy accounting (Berndt 1983). In the 1970s as a result of the oil crisis the concept of net energy drew some economists' attention. For example, Odum (1973) applied the concept of "net energy" to the energy balance in a society, considering it after subtracting "the costs of getting and concentrating this energy".

Since the 1970s the concept of "net energy" has been applied to different fields (Hernandez and Kenny 2010). The net energy analysis is defined as a "technique for evaluating which seeks to



[2] Technical Alliance is a group of engineers, scientists, and technicians based in New York formed in the 1920s; conducted an Energy Survey of North America (Burris 1993).

compare the amount of energy delivered to society by a technology to the total energy required to find, extract, process, deliver, and otherwise upgrade that energy to a socially useful form" (Cleveland and Costanza 2006), which is rather close to a definition common with the one used in the built environment.

## II.1 Definitions of net-zero energy buildings

The analysis of the literature in the field has shown the lack of common understanding of the concept and, as a result, a number of approaches to define a net-zero energy building. The most cited publication - Torcellini, Pless, and Deru (2006) - gives the following definition:

> "A net zero-energy building (ZEB) is a residential or commercial building with greatly reduced energy needs through efficiency gains such that the balance of energy needs can be supplied with renewable technologies". However, the authors state that a net-zero energy building "can be defined in several ways, depending on the boundary and the metric" (Torcellini, Pless, and Deru, 2006).

The paper presents "four commonly used definitions" for NZEBs:

> "**Net Zero Site Energy:** A site ZEB produces at least as much energy as it uses in a year, when accounted for at the site.
>
> **Net Zero Source Energy:** A source ZEB produces at least as much energy as it uses in a year, when accounted for at the source. Source energy refers to the primary energy used to generate and deliver the energy to the site. To calculate a building's total source energy, imported and exported energy is multiplied by the appropriate site-to-source conversion multipliers.
>
> **Net Zero Energy Costs:** In a cost ZEB, the amount of money the utility pays the building owner for the energy the building exports to the grid is at least equal to the amount the owner pays the utility for the energy services and energy used over the year.
>
> **Net Zero Energy Emissions:** A net-zero emissions building produces at least as much emissions-free renewable energy as it uses from emissions-producing energy sources" (Torcellini, Pless, and Deru, 2006).

From these four definitions it can be concluded that in order to define a NZEB it is necessary, first, to understand the aim of such a definition and target audience (e.g. reduce energy consumption of a household, promote a policy instrument, create the incentives for corporate actors, etc.) and, second, set the system boundaries (e.g. consider only the energy consumed and produced in the building or take into account also the energy supplied through the grid). Crawley et.al. point out that “agreeing to a common definition of NZEB boundaries and metrics is essential to developing design goals and strategies” (Crawley, Pless, and Torcellini 2009). In this regard the authors further developed the classification of NZEB definitions provided by Torcellini, Pless, and Deru (2006) on the basis of renewable energy sources (RES) applicable for buildings, and presented in a more comprehensive way. An updated classification includes four types of NZEBs ranging from NZEB A to NZEB D depending on the type of RES and its/their location in respect of the building. Table 1 resents a link between four definitions of NZEBs proposed in Torcellini, Pless, and Deru (2006) and four NZEB types developed in Crawley, Pless, and Torcellini (2009). Table 1 shows that there are two main categories of RE supply options for NZEBs: on-site and off-site. Basically, it referrers to the place where renewable energy comes to a building: either it is produced on the building site or supplied from the outside of the building through a distribution system. Column 3 gives examples of RES technological solutions, which can be applied in each NZEB type. Column 4 discusses the ability of each type to meet the site, source, emissions, and cost definitions of NZEBs.

Giving such a complex classification the authors, however, state that “there is no “best” definition or energy-use accounting method; each has merits and drawbacks, and the approach for each project should be selected to align with the owner’s goals” (Crawley, Pless, and Torcellini 2009). Crawley, Pless, and Torcellini (2009) also emphasize one common design rule applicable to all NZEB types and definitions: “tackle *demand* first, then *supply*”. It means that in order to achieve net zero energy balance in a building it is necessary, first, to reduce its energy consumption and energy losses by means of energy efficiency measures (such as daylighting, insulation, passive solar heating, high-efficiency equipment, natural ventilation, evaporative cooling, etc.) and only then establish energy supply through renewable energy sources.

This classification is further expanded and NZEB types are discussed in more details in Pless and Torcellini (2010). The authors rank the renewable energy supply options presented in Table 1 from 0 to 4. “This hierarchy is weighted toward RE technologies that are available within the building footprint and at the site”, therefore, the options which are available within a building footprint together with high energy efficiency of a building (Option 0 and 1) are the most preferable (Pless and Torcellini 2010). In case some conditions (e.g. a building is very high) do not allow a building to become a net-zero energy through utilization of these measures, other options should be used.

Table 1. Classifying NZEBs by Renewable Energy Supply

| ZEB Type | ZEB Supply-Side Options | Examples of applicable RES technologies | ZEB Definitions |
|---|---|---|---|
| ***On-Site Supply Options*** | | | |
| **A** | Use renewable energy sources available within the building's footprint and directly connected to the building's electrical or hot/chilled water distribution system | Photovoltaic, solar hot water, and wind located on the building; geothermal, buried air ducts, biomass if the building is not in a dense down-town area | YES: Site, Source, Emissions Difficult: Cost If the source and emissions multipliers for a ZEB:A are high during times of utility energy use but low during times the ZEB is exporting to the grid, reaching a source or emissions ZEB position may be difficult. Qualifying as a cost ZEB may be difficult depending on the net-metering policies in the area. |
| **B** | Use renewable energy sources as described in ZEB:A and Use renewable energy sources available at the building site and directly connected to the building's electrical or hot/chilled water distribution system. | Photovoltaic, solar hot water, low-impact hydroelectric, and wind located on parking lots, adjacent open space, but not physically mounted on the building, geothermal, buried air ducts | YES: Site, Source, Cost, Emissions Difficult: Cost If the source and emissions multipliers for a ZEB:B are high during times of utility energy use but low during times the ZEB is exporting to the grid, reaching a source or emissions ZEB position may be difficult. Qualifying as a cost ZEB may be difficult depending on the net-metering policies in the area |
| ***Off-Site Supply Options*** | | | |
| **C** | Use renewable energy sources as described in ZEB:A; ZEB:B, and ZEB:C and Use renewable energy sources available off site to generate energy on site and directly connected to the building's electrical or hot/chilled water distribution system. | Biomass, wood pellets, ethanol, or biodiesel that can be imported from off-site, or collected from waste streams from on-site processes that can be used on-site to generate electricity and heat | YES: Site, Difficult: Source, Cost, Emissions A ZEB:C source and emission position may be difficult if carbon-neutral renewables such as wood chips are used or if ZEB has an unfavorable source and carbon multipliers. This can occur if a ZEB exports energy during times that the utility has low source and carbon impacts, but imports energy when the utility has high source and carbon impacts. ZEB:C buildings typically do not reach a cost ZEB position because renewable materials are purchased to bring on-site—it would be very difficult to recoup these expenses by any compensation received from the utility for renewable energy generation. |
| **D** | Use renewable energy sources as described in ZEB:A, ZEB:B, and ZEB:C and Purchase recently added off-site renewable energy sources, as certified from Green-E (2009) or other equivalent renewable-energy certification programs. Continue to purchase the generation from this new resource to maintain ZEB status. | Utility-based wind, photovoltaic, emissions credits, or other "green" purchasing options. All off-site purchases must be certified as recently added renewable energy (Green-E 2009). A building could also negotiate with its power provider to install dedicated wind turbines or PV panels at a site with good solar or wind resources off-site. In this approach, the building might own the hardware and receive credits for the power. The power company or a contractor would maintain the hardware | YES: Source, Emissions NO: Site, Cost ZEB:D buildings may qualify as source and emissions if they purchase enough renewable energy and have favorable source and emissions factors. They will not qualify as site and cost |

**Source**: adapted from (Crawley, Pless, and Torcellini 2009)

Option 0 points out the priority of implementing energy efficiency strategies. Option 1 includes all the RES located on the building's footprint, most typical among them are PV and solar thermal systems. Option 2 also includes the RES applications installed on the building's site (property boundary). However, none of these options account for the energy which is imported from outside the building. Options 3 and 4 besides those available in Options 0, 1, 2 also include off-site RE sources that can be imported on site, and then used to generate energy (e.g. wood pellets, ethanol, and biodiesel; methane from human and animal waste treatment processes, recovery of waste energy streams from industrial processes, or landfill gas collection if they are available over the life of the building). The energy generated off-site and transported to the site is considered only under Option 4, and not included in Option 3. Option 4 is the most dubious in respect of truly net-energy building as it allows not producing but buying off-site renewable energy and renewable energy credits (RECs)[3]. As Pless and Torcellini (2010) have noted, if a building purchases all its renewable energy, it has little incentives to reduce building loads. Moreover, according to this definition, it can be qualified as NZEB even if it consumes a lot of fossil fuels. Therefore, this type of NZEBs is the least preferable. However, it may be a possible and a more sustainable solution for the buildings in a dense down-town area where the sky view factor is limited (no solar access for low buildings, not enough roof area for collectors or PV arrays in case of a tall building) and, therefore, NZE goal is unlikely to be achieved through other options.

Pless and Torcellini (2010) have connected the A-D classification proposed in Crawley, Pless, and Torcellini (2009) with 0-4 RE supply options. Basically, NZEB A from Crawley, Pless, and Torcellini (2009) presumes utilization of Option 0, NZEB B – Option 1, NZEB C – Option 3 and

[3] "A renewable energy credit is an environmental commodity that represents the added value, environmental benefits and cost of renewable energy above conventional methods of producing electricity, namely burning coal and natural gas" (Renewablechoice 2011)

NZEB D – Option 4. The linkage to the four definitions presented by Torcellini, Pless, and Deru, (2006) remains very similar to what is given in Table 1.

Therefore, the three works discussed above Torcellini, Pless, and Deru, (2006), Crawley, Pless, and Torcellini (2009) and Pless and Torcellini (2010) present the development of a comprehensive classification of NZEBs, which is often cited in the literature in this field (see Malin and Boehland 2005, Hernandez and Kenny 2010, Marszal et al. 2011, Centerline 2008, Marszal and Heiselberg 2009). There are other definitions present in the literature, which, however, are not based on classification systems.

For example, Mertz, Raffio, and Kissock (2007) considers only two definitions of ZEB: a net-zero energy building and a $CO_2$ neutral building. A net-zero energy building is "a home, that over the course of year, generates the same amount of energy as it consumes. A net-zero energy home could generate energy through photovoltaic panels, a wind turbine, or a biogas generator (however, the last two options are more applicable in rural rather than in urban areas). The net-zero energy home considered in this paper uses photovoltaic panels (PV) to offset electricity purchased from the grid" (Mertz, Raffio, and Kissock 2007).

A $CO_2$ neutral building is a building whose operation does not add carbon dioxide to the atmosphere. "This could be accomplished by purchasing tradable renewable certificates (TRC's) generated by solar, wind, or biogas. It could also be accomplished by purchasing $CO_2$ credits on a carbon trading market. In addition, the home could generate all of its energy on-site like a net-zero energy home" (Mertz, Raffio, and Kissock 2007). Therefore, according to Mertz, Raffio, and Kissock (2007), a $CO_2$ neutral building is at the same time a net-zero energy building, but a net-zero energy building is not necessarily $CO_2$ neutral.

Laustsen (2008) also provides two main definitions in relation to NZEB discussion, which are similar to the one given in Mertz, Raffio, and Kissock (2007). The first one considers zero net energy buildings as "buildings that over a year are neutral, meaning that they deliver as much energy to the supply grids as they use from the grids". Therefore, the author allows the opportunity for a net-zero energy building to consume energy from the grid. He emphasizes that in the absence of a determined definition of ZEB (which, in his opinion, "do not use fossil fuels but only get all their required energy from solar energy and other renewable energy sources"), "a traditional building, which is supplied with very large solar collector and solar photo voltage systems" can also become a zero-energy building if "these systems deliver more energy over a year than the use in the building" (Laustsen 2008).

The second definition is given for zero carbon buildings, which are "buildings that over a year do not use energy that entails carbon dioxide emission". In this regard, the main difference between zero net energy and zero carbon buildings is that the latter can consume energy from some carbon free sources, which, however, are not applicable to zero net energy houses, "such as large windmills, nuclear power and PV solar systems which are not integrated in the buildings or at the construction site" (Laustsen 2008). Therefore, if a building is net zero energy it does not automatically mean that it is zero carbon and vice versa. However, a building can comply with both definitions at the same time.

A different aspect of the NZEB concept is touched upon in the definition provided by Kilkis (2007). The author points out the importance of exergy[4], meaning that energy received by a NZEB from and supplied to the grid should be the same quality. Kilkis states that in practice a NZEB can supply to the district energy the same amount of heat it received but at lower

[4] "Exergy is defined as the maximum amount of work that can be done by a subsystem as it approaches thermodynamic equilibrium with its surroundings by a sequence of reversible processes." (Szargut, Morris, and Steward 1988)

temperature, creating a negative exergy balance which has to be covered by "additional fuel spending and harmful emissions" (Kilkis 2007).

In this regards, Kilkis develops a new definition of a net-zero exergy building as "a building, which has a total annual sum of zero exergy transfer across the building-district boundary in a district energy system, during all electric and any other transfer that is taking place in a certain period of time". According to Kilkis, the key advantage of such an approach is that it gives the opportunity to estimate an overall building's impact on the environment through quantifying the compound emissions[5] of a building. Therefore, the author argues that the implementation of the net zero energy concept in buildings without including an exergy dimension is insufficient for tackling global climate change challenge.

There is a number of definitions of NZEBs, which include different aspects depending on the goal of the project, local conditions, budget available for a NZEB project, etc. It is very important to know and take into account these aspects in order to define a NZEB accurately. Some of these aspects are derived from the literature, for example, from Marszal et al. (2011) and Marszal and Heiselberg (2009) and presented in the following section.

## II.2 The main aspects of NZEBs

This section presents the key NZEBs features, which can vary from project to project, requiring the application of different NZEB definitions and analytical approaches, and even design and technological solutions. Taking into account each of these aspects helps to create a definition of a NZEB appropriate for each specific project or task. The NZEB features discussed here are:

- Indicator of the balance

[5] Compound emissions are direct carbon emission from the building plus avoidable secondary carbon emissions caused by exergy mismatch (Kilkis 2007).

- Period of the balance
- Purpose of energy use
- Connection with the energy infrastructure
- Renewable energy supply
- Energy efficiency requirements
- Building type

### II.2.1 Indicator of the balance

As has been shown in the previous section, the concept of net zero balance can be applied to different building indicators, such as final energy use, primary energy use, $CO_2$ emissions, exergy, costs. Definitions of NZEBs, outlined above, proposed by Torcellini et al. (2006), Kilkis (2007), Laustsen (2008), Mertz, Raffio, and Kissock (2007), etc., use different metrics.

If energy use is considered as an indicator the main question to be answered is whether final or primary energy is analyzed. For example, EPBD uses primary energy use as a metric of the balance for “nearly zero-energy buildings” (The European Parliament 2010). According to the review of calculation methodologies for zero energy buildings presented in Marszal et al. (2011), “the primary energy clearly is the most favoured metric of the net ZEB balance”.

Hernandez and Kenny (2010) and Leckner and Zmeureanu (2011) also use primary energy as the indicator for the annual energy use. Hermandez et.al. point out the advantage of this indicator as “primary energy allows differentiation between electricity and fossil fuel use and includes an indication of the efficiency of delivering heating, hot water, lighting, etc” (Hernandez and Kenny 2010).

### II.2.2 Period of the balance

The period for which net zero balance is calculated plays an important role in NZEBs' analysis. The possible periods include: one year, one month, lifetime of a building, operating time of a building (Marszal et al. 2011). It is obvious that applying different approaches to the same building may give different results. For example, an annual energy balance could show that the building meets net zero energy requirements, while its energy consumption during some months may exceed energy production.

Annual energy balance is the most commonly used approach in the NZEB analysis. It is used in a number of literature sources and projects (e.g. Mertz, Raffio, and Kissock 2007, Noguchi et al. 2008, IEA/OECD 1995, Torcellini and Crawley 2006, Iqbal 2004, Esbensen and Korsgaard 1977, Rosta et al. 2008, Wang, Gwilliam, and Jones 2009).

A more complex methodology presumes the calculation of energy balance in a building taking the whole life cycle of a building into account (Hernandez and Kenny 2010). It is pointed out by the authors that none of the studies in the field of NZEBs uses the life cycle perspective as a basis for energy balance calculation. However, there is a study Leckner and Zmeureanu (2011), which was published after Hernandez and Kenny (2010), and which presents life-cycle energy and costs analysis for a building in Montreal. This demonstrates that the life-cycle approach is applicable in the field of NZEBs analysis and might become even more popular.

Monthly energy balance is not a very common approach, however, some studies use it in their analysis (e.g. Iqbal 2004, Christian 2005, Bojic et al. 2011, Miller and Buys 2010).

### II.2.3 Purpose of the energy use

According to Marszal et al. (2011) most of the studies in the field do not specify what end-uses are taken into account in the net energy balance calculation. However, according to the author, it makes sense to include in the analysis all the main end-uses: heating, cooling and dehumidification, ventilation and humidification, hot water and lighting (Marszal et al. 2011).

Early studies in the field (Besant, Dumont, and Schoenau 1979, Bliss 1955, Saitoh, Matsuhashi, and Ono 1985, Esbensen and Korsgaard 1977) did not consider all the end-uses, typically concentrating on the energy use for space heating and/or hot water supplied by solar energy technologies, therefore, not dealing with net zero energy buildings, but with "zero-thermal" buildings (Marszal et al. 2011, Hernandez and Kenny 2010).

In contrast, the recent approach to NZEBs analysis tends to cover not only the operational energy of all the end-uses in the building, but also the energy embodied in building materials, construction and delivery processes. This, obviously, makes the analysis much more complicated. The supporters of this approach argue that such a life-cycle perspective gives the opportunity to estimate the real impact of a building on the environment while the analysis of only operational energy use is insufficient to determine whether the building is net zero energy (Hernandez and Kenny 2010). In this regard, they propose their own definition of a net zero energy building – life-cycle zero energy building (LC-ZEB). "A LC-ZEB is one where the primary energy used in the building in operation plus the energy embodied within its constituent materials and systems, including energy generating ones, over the life of the building is equal to or less than the energy produced by its renewable energy systems within the building over their lifetime" (Hernandez and Kenny 2010).

### II.2.4 Connection with the energy infrastructure

There are two possible types of NZEBs: those that are connected to the energy infrastructure and those that are not connected. Energy infrastructure in the literature is usually devoted to the electricity grid, district heating and cooling systems, gas pipe network, biomass and biofuels distribution networks (Marszal et al. 2011). In this regards, these two types of NZEBs are often called on-grid (or grid-connected, or grid-integrated) and off-grid (or energy autonomous, energy self-sufficient or stand alone) buildings.

The main difference between these two types of NZEBs is that the first has the opportunity to take energy from and give energy to the grid, while the second has to produce and consume all the energy by itself on the building's site. However, in both cases the energy consumption should be covered by renewable energy supply for a certain time scale.

Connection to the grid allows a building to exchange energy with it when it is needed: for example, when a building needs more energy than it can produce, it can get the required energy from the grid. The opposite situation is also possible: when a building produces more energy than it needs, it can supply the surplus to the grid. In both situations the building can be net zero energy on an annual basis. Therefore, the electricity grid may be considered as a means of energy storage. In off-grid buildings there is no such an opportunity, thus, other (usually more expensive and space-consuming) means of energy storage should be applied (e.g. water tanks or thermal mass). Another drawback of energy autonomous houses is that the lack of energy storage may lead to oversizing of renewable energy systems in order to meet a peak energy demand (Torcellini, Pless, and Deru, 2006, Voss et al. 1996, Iqbal 2004).

Table 2 presents some definitions for the NZEBs connected and not connected to the energy infrastructure.

Table 2. Definitions for on-grid and off-grid NZEBs

| Definitions of on-grid NZEBs | Definitions of off-grid NZEBs |
|---|---|
| “*Zero Net Energy Buildings are buildings that over a year are neutral, meaning that they deliver as much energy to the supply grids as they use from the grids. Seen in these terms they do not need any fossil fuel for heating, cooling, lighting or other energy uses although they sometimes draw energy from the grid”* (Laustsen 2008) | *”Zero Stand Alone Buildings are buildings that do not require connection to the grid or only as a backup. Stand alone buildings can autonomously supply themselves with energy, as they have the capacity to store energy for night-time or wintertime use.”* (Laustsen 2008) |
| “*In a zero energy home no fossil fuels are consumed and its annual electricity consumption equals annual electricity production. “A grid-connected zero energy home may generate more power than it uses supplying excess generated power to the grid. During times of power outage, using the energy stored in batteries, a grid-connected zero energy home can generate its own power, allowing the homeowner essential energy security”*(Iqbal 2004) | “*An off-grid zero energy home has an arrangement for large energy storage usually in the form of batteries. In an off-grid zero energy home, depending upon the battery storage, a part of the load may be un-served”* (Iqbal 2004) |
| “*A zero energy house is defined here as a house in which no fossil fuels are consumed, and the annual electricity consumption equals annual electricity production”. “…the electricity grid acts as a virtual buffer with annually balanced delivers and returns”* (Gilijamse 1995) | *“An "autonomous house" is defined as a house that can function independently of support and services from public facilities”. “This type of house did not need to be connected with such services as gas, water, power, or sewers; it used alternative energy, such as solar power or wind power and could treat its own wastewater and sewage”* (Chen et al. 2009) |
| “*During times of peak demand, a Zero Energy Home generates more power than it uses, thereby reducing power demand on the utility provider. During times of power outage, the home generates its own power, allowing the homeowner essential energy security”*(Parker, Thomas, and Merrigan 2001) | *“Autonomous house is a dwelling unit independent from the urban infrastructure such as electricity grid, sewage grid, etc. It is supposed to provide its own electricity, autonomous passive heating and cooling, make use of its grey water, as well as of rainwater, takes care of its sewage, produce compost, and in some more radical cases be independent from the food supply system”* (Mrkonjic 2006) |

The literature provides a number of examples for both grid-connected (Noguchi et al. 2008, Zhu et al. 2009, Parker, Thomas, and Merrigan 2001, IEA/OECD 1995, Gilijamse 1995, Platell, and Dudzik 2007, Hamada, et al. 2000, Iqbal 2004, Wang, Gwilliam, and Jones 2009, Bojic et al. 2011, Christian 2005, Deng, Dalibard, et al. 2011, Tse and Fung 2007) and energy self-sufficient NZEBs (IAAC | MIT’s CBA | FabLab 2010, Pichler 2009, Mrkonjic 2006, Abegg 2010, Miller and Buys 2010, Dalton, Lockington, and Baldock 2008) (for more details see Section II.5).

### II.2.5 Renewable energy supply

As the essence of a NZEB concept presumes that building's energy use is covered by renewable energy production, and, therefore, the supply options in NZEBs are inevitably related to renewable energy sources (RES). RES, which can be utilized in buildings may include: solar, wind, geothermal, wave, hydro energy and biomass.

As has been shown earlier, in respect of energy supply in the NZEBs Torcellini, Pless, and Deru, (2006) distinguish between on-site and off-site buildings. Table 1 gives examples of renewable energy supply systems for both types. Summing up, on-site energy supply is usually provided by photovoltaic, solar collectors for hot water and/or space heating and/or cooling, on-site wind or mini hydroelectric installations - mostly in rural areas. Some studies also consider the installation of heat pumps to supply additional energy for NZEBs (Deng, Dai, et al. 2011, Biaou and Bernier 2008, Bojic et al. 2011, Deng, Dalibard, et al. 2011).

Off-site energy supply options include any energy sources which can be transported to the building to generate energy on-site, such as biomass, wood pellets, ethanol, biodiesel or any purchases of renewable energy produced outside the building's site.

The most applicable and widely used energy supply options are those utilizing solar energy on the building's site, i.e. solar collectors and photovoltaic. Most of the literature sources cited earlier as examples of on- and off-grid NZEBs and all the buildings presented in US DOE (2008) use these solar technologies. Examples of studies considering wind as an energy supply option for NZEBs include: Iqbal (2004), Wang, Gwilliam, and Jones (2009), Hamada, et al. (2001), Bagci (2009), Dalton, Lockington, and Baldock (2009). Wood is used to produce energy, for example, in the Aldo Leopold Legacy Center in US (US DOE 2008). Bagci (2009) also considers tidal, wave, energy crops and municipal solid waste as potential renewable energy supply options for NZEBs.

### II.2.6 Energy efficiency requirements

Renewable energy supply often goes in combination with the improvement of energy efficiency in order to reduce energy consumption and achieve net zero energy balance. The necessity of energy efficiency strategies in NZEBs is emphasized in Torcellini, Pless, and Deru (2006), Pless and Torcellini (2010), Crawley, Pless, and Torcellini (2009), Laustsen (2008), Tait (2006), Charron, Athienitis, and Beausoleil-Morrison (2005), Iqbal (2004), Tse and Fung (2007). Energy efficiency measures usually include those applied in the passive houses, description of which can be found , for example in Feist, Peper, and Görg (2001) and Feist et al. (2001).

### II.2.7 Building type

Building type is usually specified not in the general definitions of NZEBs, but in the description of a concrete project. Explanation for this is that NZEBs concept requires that net energy balance of a building must be zero regardless of its building type. However, the technological and design solution may differ in residential and commercial buildings, thus, it is important to specify the building type for a certain project to demonstrate that this type of buildings can achieve net zero energy balance.

The studies available in the field show that NZEBs exist both in residential and commercial sectors (see also Section II.5). However, most of the studies cited here analyze residential buildings. Due to this reason, these publications use the term (net) zero home or house instead of building. Among them only Dalton, Lockington, and Baldock (2008) and Dalton, Lockington, and Baldock (2009) study a net-zero energy hotel and tourist accommodation, respectively. The zero-energy buildings database US DOE (2008) presents eight case-studies for commercial and institutional buildings, including office, recreation and education buildings.

## II.3 Technological approaches used in NZEBs

Technological solutions in buildings play a major role in achieving net zero energy goal. They vary among climate zones, design and architectural preferences, building types, project goals, target audience, etc. However, perhaps one of the most important factors to be taken into account is the definition chosen for NZEBs.

Table 1 shows that different definitions of NZEBs require different technologies to be applied. In this section, in order to focus and limit the discussion, only the technologies, which can be installed on a building's site, are considered. It means that off-site renewable energy supply options such as solar power plants, large-scale wind mills, hydro-electric power station, wave and tidal energy installations, etc., which are located outside the building are not taken into account.

As has been shown in Section II.2.6, the optimal strategy for a NZEB is a combination of energy efficiency measures with renewable energy supply. This section follows this principle and, first of all, presents how energy use in buildings can be reduced through energy efficiency improvement and, secondly, provides the overview of possible technological solutions, which can be used in the building to cover the rest of energy use with renewable energy supply.

### II.3.1 Overview of the key energy efficiency measures

According to Feist, Peper, and Görg (2001), the crucial features of energy efficient houses ("passive house"[6] in their terms) are:

- Superinsulation
- Combining efficient heat recovery with supplementary supply air heating
- Passive solar gain[7]

The authors point out that minimizing of a building's environmental impacts, however, requires two additional elements:

1) Energy efficient appliances
2) Meeting the remaining energy demand with renewable energy (Feist, Peper, and Görg 2001)

As application of these features considerably reduces energy use in passive houses, they are also appropriate to reduce energy demand in NZEBs. Below building where energy efficiency measures are implemented are referred as energy efficient buildings.

Each of requirements outlined by Feist, Peper, and Görg (2001) can include several energy efficiency measures, which play different roles in buildings. Table 3 presents key energy efficiency strategies and their roles in buildings.



[6] "A passive house is a building in which a comfortable interior climate can be maintained without active heating and cooling systems. The house heats and cools itself, hence, the term "passive" (Feist 2006).

[7] Passive solar gain here means directing of solar heat through windows and the building's surfaces without any additional technologies or devices

Table 3. Main energy efficiency measures and their roles in buildings

| Energy efficiency measures | Role in the building | | | |
|---|---|---|---|---|
| | **Energy losses reduction** | **Renewable resources use** | **Energy loads reduction** | **Indoor comfort improvement** |
| **Orientation and shape of the building** | √ | √ | √ | √ |
| **Advanced insulation** | √ | | √ | √ |
| **Reduced thermal bridging** | √ | | √ | √ |
| **Air tightness** | √ | | | √ |
| **Use of thermal mass** | √ | | √ | √ |
| **Advanced windows** | √ | √ | √ | √ |
| **Shading** | √ | √ | √ | √ |
| **Cool, white roofs** | | √ | √ | √ |
| **Daylighting** | | √ | √ | √ |
| **Ventilation strategies** | √ | √ | √ | √ |
| **Energy efficient lighting** | | | √ | √ |
| **Energy efficient appliances** | | | √ | |

Key energy efficiency measures are briefly described below.

### II.3.2 Orientation and shape of the building

Usually a rectangular floor shape is chosen for energy efficient buildings with the façade oriented to the south in the Northern hemisphere (to the north in the Southern hemisphere) it helps to maximize heat gains from the sun and reduce heating needs in winter. East orientation (for the Northern hemisphere) may also be appropriate as it helps to heat a house early in the morning and avoid overheating by direct sunlight in the afternoon (Charron and Athienitis, 2006). However, Robertson (2003) states that buildings with a north-south long axis orientation have greater potential for overheating in the non-heating season and get little advantage from solar heat gain in the winter.

A significant windows area should be placed on the wall oriented towards Equator in order to maximize passive solar gains (Strom, Joosten, and Boonstra 2005). However, the glazed area must be harmonized with the amount of thermal mass in the building (Charron and Athienitis, 2006).

A building's size also affects the energy demand in the building. A two-story compact house may be more efficient than a single-story house since its exterior building envelope is smaller per unit size of floor space (Charron and Athienitis, 2006).

Together with the building design and orientation the materials, which are used in the building, play a crucial role (in optimizing heat gains and losses and maintaining internal comfort for example, through amount of thermal mass in the building) (Graham 2003). For more detailed discussion on the concept of thermal mass - see also Section II.3.6.

### II.3.3 Advanced insulation

The main function of good insulation (sometimes called superinsulation) of a building is to minimize heat losses through exterior elements (e.g. walls, windows, roof), which may account for 50% of total heat losses in the building. Usually a thicker layer of insulation is applied for the roof and thinner, for example, for the floor slab as the temperature difference with outdoor air is much great than with the soil (Feist, Peper, and Görg 2001).

Harvey (2010) provides the following types of insulation:

- Glass fibre (fibreglass) batts
- Mineral fibre batts
- Cellulose
- Foam
- Wood
- Vacuum insulation panels

Feist, Peper, and Görg (2001) also provide a wide range of insulation options: web beams, cellulose, polystyrene, timber, hemp wool and natural gypsum. However, it is not the purpose of this work to consider these types in details.

### II.3.4 Reduced thermal bridging

Thermal bridges are "areas where the regular construction of external building elements is disturbed" (Feist, Peper, and Görg 2001). Thermal bridges are responsible for significant heat losses from the building, thus, certain measures should be applied in order to reduce them. Feist, Peper, and Görg (2001) propose the following rules for tackling the thermal bridges problem:

> **Prevention rule**: Where possible, do not interrupt the thermal envelope.
>
> **Penetration rule**: Where an interrupted insulating layer is unavoidable, thermal resistance in the insulation plane should be as high as possible; this indicates use of e.g. aerated concrete or, better still, timber instead of normal concrete or sand-lime bricks.
>
> **Junction rule**: At building element junctions, insulating layers should meet without any gaps. Insulating layers should join without interruption or misalignment.
>
> **Geometry rule**: Design edges should have as obtuse angles as possible.

The authors state that if these four rules are applied in the right way, the heat losses through thermal bridges will be considerably reduced and a building's envelope can be called 'thermal-bridge-free' (Feist, Peper, and Görg 2001).

### II.3.5 Air tightness

Air tightness is the resistance of the building envelope to inward or outward air leakage. Excessive air leakage increases energy consumption and draughts in buildings (HRS Services Ltd 2010). Therefore, air tightness of the building envelope is very important in an energy efficient building, especially at connections between different elements, (e.g. windows, doors) (Strom, Joosten, and Boonstra 2005).

Feist, Peper, and Görg (2001) propose to improve air tightness through “the principle of a single airtight envelope”. This principle requires that the envelope “encloses the entire interior space”. This can be achieved by applying different technologies for insulation and air leakage prevention, such as: internal plastering (lime plaster, lime-cement plaster, gypsum plaster, also reinforced loam plaster); plywood board, hardboard, particle board, bituminous reinforced felt and tear-proof reinforced building paper (Feist, Peper, and Görg 2001).

### II.3.6 Use of thermal mass

Thermal mass is the ability of building materials to store heat (thermal storage capacity). The main importance of materials with thermal mass for an energy efficient building is their ability to absorb heat, store it, and release it later (SEA Victoria 2005).

Examples of thermal mass may be: parts of the building structure (walls, floors, ceilings, stairs, etc), furniture, finishing materials and passive solar heat storage containers (Kosny 2001).

Utilization of thermal mass reduces heating and cooling loads, temperature swings and improves thermal comfort in the building (Charron and Athienitis, 2006, Kosny 2001).

Kosny (2001) and SEA Victoria (2005) state that utilization of heavyweight construction materials with high thermal mass can significantly reduce total energy consumption in buildings. However, the amount of thermal mass should be optimized, taking into account the amount of glazing Charron and Athienitis (2006) and climate conditions, as its excess may increase winter heating needs of the building, especially if the opportunity of direct solar gains is limited (SEA Victoria 2005).

The location of thermal mass should also be taken into account. For example, it stores and releases more heat if it is directly heated by the sun, especially in winter (Chiras 2002). At the same time the effectiveness of thermal mass decreases significantly if the insulation from external temperatures is poor. Therefore, thermal mass should be located within insulated walls close to the inner surfaces (SEA Victoria 2005).

The effectiveness of thermal mass also depends on climate. It is more effective in places where there is a big difference in the maximum day temperature and minimum night temperature. Generally, the greater the daily temperature range, the more thermal mass is needed in the building (SEA Victoria 2005).

### II.3.7 Advanced windows

The role of windows in an energy efficient building should not be underestimated. Advanced energy efficient windows perform such functions as (1) daylighting, (2) solar heat gaining and (3) heat losses reduction. Daylighting allows for maximum utilization of natural light for lighting the room and decrease the operation time of bulbs and lamps in the building, therefore, reducing energy consumption. The second function is a part of passive solar heating as it allows sun heat to enter the building directly, which is then captured and stored by thermal mass. However, windows also should prevent overheating through solar heat gain, for example, in summer or hot climates. The third function is also a key requirement for advanced windows as it prevents the captured solar heat from leaving the building.

In order to perform these functions successfully, windows should meet several requirements in relation to their location in the building, design and materials used. As has been noted earlier, the best location of the windows is the Equator-facing wall. As for window's design, Feist, Peper, and Görg (2001) recommend using triple low-emissivity (low-e) glazing or evacuated double glazing in order to minimize energy losses from windows. In such windows there are three or two glazings and the interspace between them is filled with heavy noble gases. Moreover, the surfaces facing towards the interspace are coated with an infrared-reflecting material in order to reduce heat transfer from inside to outside of the building. Special coating also improves passive solar gains through the window. The authors also point out the necessity for high thermal insulation of window frames. They give the examples of both wooden and plastic frames with good insulation and recommend increasing the depth to which the glazing is inserted in the frame in order to reduce thermal bridging through the glazing edges (Feist, Peper, and Görg 2001).

Trombe walls also use such advanced window design to provide solar passive heating. This is a south-facing wall (north-facing for the Southern hemisphere) with a glazed external surface and reduced heat losses to outside. At the top and bottom of the trombe walls are ventilation openings which allow heated air to circulate and increase the air temperature of the interior space (Strom, Joosten, and Boonstra 2005). However, Charron and Athienitis (2006) referring to the Canada Mortgage and Housing Corporation, state that trombe walls are not effective in colder climates due to limited insulation, which results in significant heat loss at night.

Reduction of heat losses through windows by means of low-e coating is more appropriate for cold climates, while in hotter conditions "low-gain" or "spectrally selective" glazings may be more favorable. However, these types of glazing also reduce passive solar heating in winter (Apte, Arasteh, and Huang 2003)

Therefore, the effectiveness of advanced windows is climate dependent. Existing solutions can perform well either in heating- or cooling-dominated climates, but not in both (Apte, Arasteh, and Huang 2003). In this regard, Apte, Arasteh, and Huang (2003) argue that modern window technologies and design are unable to meet the requirement of NZEBs. The authors point out the necessity for new technological solution for windows in NZEBs. They propose that one of the possible solutions can be dynamic fenestration systems that could "optimize a window's solar gain characteristics according to weather conditions, taking advantage of passive solar effects in winter and rejecting unwanted solar heat gain in summer" (Apte, Arasteh, and Huang 2003). However, the solution presented in this study is a future technology, which is not available on the mass market yet. According to the authors, the existing technologies closest to their system are those that enable windows to have dynamic properties, such as electrochromic glazing, operable shading systems, and light-redirecting devices. These options allow the glazing to either change its transparence, according to outdoor conditions, or distinguish between winter and summer sun, transmitting the former and reflecting the latter (Apte, Arasteh, and Huang 2003).

### II.3.8 Shading

However, while the dynamic glazing systems are not widely spread on the market, there are other strategies, which give the opportunity to control the amount of solar gain, especially in summer or hot climates. One such strategy is shading. Shading is any kind of protection of the solar transmitting surfaces of the building (usually glazing) from direct sunlight (Colt International Ltd 2003). Shading minimizes the incident solar radiation and prevents the building from overheating and, consequently, improves building energy performance (Kamal 2010).

Shading may be natural (trees, bushes, etc.) or artificial (e.g. overhangs, louvers, awnings, internal blinds, controllable fins, etc). Natural shading is probably the easiest, most environment-friendly and cheapest way to avoid unwanted solar heat gain. It presumes that passing of direct sunlight through the roof, walls and glazing is blocked by trees or other vegetation.

Kamal (2010) provides the following rules for natural shading:

- Deciduous trees and shrubs provide summer shade and allow winter access. The best locations for them are on the south and southwest side of the building.
- Trees with heavy foliage are very effective in obstructing the sun's rays and casting a dense shadow.

- Evergreen trees on the south and west sides provide the best protection from the setting summer sun.
- Shading and insulation for walls can be provided by plants that adhere to the wall (e.g. English ivy) or by plants supported by the wall (e.g. jasmine).

However, if natural shading is not applicable or insufficient, the artificial shading can be used. There are different types of artificial shading devices. One of the classifications is:

- Movable opaque: Roller blind curtains, awnings etc. reduce solar gains but impede air movement and cut the view.
- Louvers: They are adjustable or can be fixed. To a certain extent impede air movement and provide shade to the building from the solar radiation.
- Fixed: Overhangs of chajjas provide protection to the wall and opening against sun and rain (Kamal 2010).

Weston (2010) distinguishes between static and active shading devices. The main difference between static and active shading is that the latter can adapt to changing conditions, depending on lighting, time of day, and the presence of the occupants of the building. Active shading usually takes the form of motorized metal fins and roll-down shades. A new type of solar shading ("memory mesh"), which has the ability to change shape in response to solar demands, lighting needs, passive energy strategies and users' preferences, is under development at the moment (Weston 2010).

Kamal (2010) also points out the importance of roof shading. The roof may be covered with "concrete or sheet or plants or canvas or earthen pots etc". Further strategies applicable for roofs are described below, in Section II.3.9.

### II.3.9 Cool, white roofs

A cool roof is a solar-reflective roof, which absorbs less sunlight than a conventional one. The greater reflectivity is achieved by utilizing the light color of a roof surface and special highly reflective[8] and emissive[9] materials, which can reflect at least 60% of sunlight rather than 10-20%, reflected by traditional dark-colored roofs (EPA 2007).

Standard black asphalt roofs can heat up to 74 - 85°C and bare metal or metallic roofs - 66 - 77°C in hot summer day. The peak temperature for the cool roofs is only 43-46°C. Conventional roofs can be 31-47°C hotter than the air on any given day, while for cool roofs this range tends to be 6-11°C (EPA 2007).

There are two main types of cool roofs: low-sloped and steep-sloped depending on roofing material. Traditionally, low-sloped roofs use built-up roofing or a membrane, and the primary cool roof options are coatings and single-ply membranes. The most common materials for steep-sloped roofs are asphalt shingles (for more details see (EPA 2007).

The main benefit of cool roofs is that it transfers less heat to the building in summer (or in hot climates), thereby reducing cooling energy demand. Moreover, it helps to decrease a peak electricity use in commercial and public buildings, which occurs on weekday afternoons due to use of cooling, appliances and often lighting. Cool roofs can also improve human health, for example by reducing heat-related illnesses and deaths in buildings without air-conditioning (EPA 2007). However, during winter buildings with cool roofs absorb less solar heat, which reduces the passive solar heating. In climates with cloudy winters and/or hot summers this adverse winter effect is much less than the amount of cooling energy saved during summer (Wang 2008).

[8] Solar reflectance, or albedo, is the percent age of solar energy reflected by a surface (EPA 2007).

[9] Thermal emissivity is a relative term, which shows the amount of heat a surface material radiates per unit area at a given temperature, in comparison with an absolute black body, i.e. how readily a surface gives up the heat (EPA 2007).

### II.3.10 Daylighting

Daylighting is another energy efficiency measure, which can be realized through the rational design of glazing surfaces and shading. "Daylighting is the use of light from the sun and sky to complement or replace electric light" (O'Connor et al. 1997). Utilization of daylighting reduces energy use for lighting and its associated cooling, increases indoor comfort and the satisfaction of inhabitants. There are different strategies, which help to maximize the use of daylight in buildings. The main recommendations for daylighting are summarized in Table 4.

Table 4. Strategies for improved daylighting in buildings

| Area of implementation | Recommendations for increasing daylighting |
|---|---|
| **Building's shape** | • higher the skin-to volume ratio (provides the greater percentage of floor space available for daylighting);<br>• a shallow floor plate; |
| **Building's orientation** | • long axes are facing east and west;<br>• shallower spaces are placed on the north side and deeper spaces - on the south side; |
| **Windows' location** | • daylight can be transmitted inside the building;<br>• north and south locations;<br>• location near room's surfaces (provides better redistribute the daylight);<br>• horizontal roof openings (present the best daylighting performance but may cause glaring, summer overheating and winter heat loss); |
| **Windows' shape and size** | • nearly continuous strip horizontal windows;<br>• high windows (provide deeper the daylight zones);<br>• small openings rather than increasing window size (larger windows cause more glare and overheating, require more shading); |
| **Windows' glazing** | • low-e glazing with minimized heat losses should be used; |
| **Windows' views** | • complex views with changing activities should be preferred to static views; |
| **Internal space planning and design** | • spaces for the activities with higher lighting should be located nearer the windows;<br>• light for spaces should not be blocked by furniture elements;<br>• light-colored deep reveals, ceiling baffles, exterior fins, shelves, and walls;<br>• large areas of dark colors should be avoided and kept away from the windows;<br>• matte finishes should be used;<br>• light shelves[10] should be used; |
| **Devices** | • automated daylight control systems: dimming and switching should be used;<br>• dimming adjusts the light output to provide the desired light level;<br>• switching turns individual lamps on or off to provide the appropriate light level. |

**Data Sources:** based on Robertson (2003) and O'Connor et al. (1997)



[10] "This is a horizontal element with a high-reflectance upper surface that reflects light onto the ceiling and deeper into a space" (Robertson 2003)

### II.3.11 Ventilation strategies

Ventilation in energy efficient buildings is very important for providing fresh air and reducing cooling loads. There are two main types of ventilation, which can be applied in an energy efficient building: natural and forced ventilation.

Natural ventilation is possible due to pressure difference at the inlets and outlets of a building envelope and the difference between indoor and outdoor temperatures, as a result of wind velocity, while "forced ventilation is achieved by mechanical means, using fans to reach and control the appropriate air speed" (Energy Research Group, Central Institution for Energy Efficiency Education, and Architecture et Climat, Centre de Recherches en Architecture 2000). Natural ventilation usually takes place through opening windows and, therefore, causes heat losses; moreover, it does not always provide a sufficient amount of fresh air (NREL 2001). As an energy efficiency building is airtight and aims at minimizing energy losses, this method of ventilation is usually not optimal.

Feist, Peper, and Görg (2001) and Feist (2006) recommend forced ventilation with high efficient heat recovery for energy efficient buildings and/or passive houses. The main feature of such a ventilation strategy is heat exchanger. Warm exhaust air flows from the room to the heat exchanger and delivers the heat to its plates. At the same time colder fresh air enters the heat exchanger from outside the building. The heat captured on the plates is used to warm up fresh air and supply it to the room. The main advantage of the heat recovery is that exhaust and fresh air are not mixed. This principle allows for almost 100% recovery of the temperature difference, if the exchanger is long enough. Usually this percentage is between 75% and 95% (Feist 2006). This system requires regular replacement of air-filters (Strom, Joosten, and Boonstra 2005).

Energy efficiency heat recovery ventilation consumes a low amount of energy (2-7 kWh/m$^2$year) and reduces heat losses (which could take place in case of opening windows) considerably.

Charron and Athienitis (2006) also recommend to use a heat recovery ventilator and point out that its effectiveness is high – at the level of 80-85%.

Another option for energy efficient ventilation is the use of earth buried ducts. It uses the temperature difference between the outside air and ground allowing for preheating the incoming air in earth buried ducts in winter and precooling it in summer (Feist 2006).

Evaporative cooling may also be applicable for energy efficiency buildings, especially in dry climates. It performs three main functions: ventilation, cooling and humidification of the air. Hot air from outside enters the swamp cooler and passes over water-saturated pads (the atomizers are typically used), the water evaporates into the air and the energy used removes heat from the air. Much cooler air is then directed inside the building (NREL 2001).

### II.3.12 Energy efficient lighting

As has been noted above, daylighting strategies can considerably reduce energy use. In order to reduce energy use even further energy efficient bulbs and control of electric light usage can be implemented in the building.

As for the choice for bulbs, there are several main types available on the market, which perform at different efficiency levels: incandescent, discharge and light emitting diodes. Incandescent bulbs are the standard light bulbs and halogen lamps with the shortest lifetime and very low efficiency. They have the lowest investment and highest operation costs.

Discharge lamps have higher efficiency and lifetime than incandescent ones and include fluorescent tubes, compact fluorescent lamps (CFLs) and metal halide lamps. They are widely spread on the market and available at competitive prices.

The most recent lighting technology is light emitting diodes (LEDs). They have a very long lifetime and high efficiency (Adelaide City Council 2011). However, the availability of LEDs on the market is rather limited and their costs are rather high (Sustainable Victoria 2007).

Table 5 presents the data on the main characteristics of different types of bulbs. It is obvious that incandescent bulbs have to be replaced with the more efficient ones, especially in the building aiming at net zero energy status. The replacement of only 5% of all incandescent bulbs in the world (12.5 billion/year) with LEDs would save 60 TWh of electricity equivalent to 23.4 Gt of $CO_2$ a year (STMicroelectronics 2009).

Table 5. Parameters of different types of lighting

| Lamp type | Lifetime, '000 hours | Light output, Watts per '000 hours |
|---|---|---|
| **Standard light bulbs** | 10-15 | 1-2 |
| **Halogen bulbs** | 15-25 | 2-5 |
| **Fluorescent tubes** | 80-100 | 15-20 |
| **Compact fluorescent lamps** | 50-80 | 10-15 |
| **Metal halide bulbs** | 70-120 | 10-20 |
| **LEDs** | 30-70 | 20-100 |

**Source**: Adelaide City Council (2011)

Table 6. Light control strategies

| Light control strategy | Method of working |
|---|---|
| **Scheduling** | turns the light on when needed, and turn it off when not needed; includes manual (in a wall switch), automatic time clocks and occupancy and movement sensors |
| **Daylighting** | turns off the electric lighting or reduce its use if enough natural light is available (usually by means of photosensors' signals to the lighting control system) |
| **Lumen maintenance** | monitors luminance levels of lamps and increase the delivered power over their life cycle (new lamps are operated at partial power, and deteriorated lamps - at full power) |
| **Tuning** | dims lights to the lowest level that does not affect the performance in order to avoid overlighting |
| **Adaptation compensation** | reduces the visual difference (luminance variance) between the background and local (task) lighting |
| **Peak demand limiting.** | detects a building's peak energy draw and slowly reduces power to lighting systems with a minimal impact on occupants |
| **Different light levels** | distinguishes different levels of light intensity, according to the functions of space: an adequate level of background lighting and more intensive task lights |

**Data sources:** adapted from (Eley, Tolen, and Benya 1992), (Adelaide City Council 2011)

According to Eley, Tolen, and Benya (1992) control of electric light includes six basic strategies: scheduling, daylighting, lumen maintenance, tuning, adaptation compensation and peak demand limiting. They are summarized in Table 6. One more strategy - different light levels – has been added from Adelaide City Council (2011).

### II.3.13 Energy efficient appliances

As electrical energy consumed by appliances can be included into the net zero energy balance, it is quite important to reduce it. There are three ways to do this: reduce the number of appliances in the building, reduce the amount of appliances' operating time and use more energy efficient appliances. While the two first strategies can rarely be realized without decrease in inhabitants' comfort and satisfaction (although stand-by energy consumption can be reduced by unplugging appliances when they are not used), the third one is easily realized and may be quite successful.

All the main appliances used in residential and commercial buildings (refrigerators, freezers, dishwashers, clothes washers, ovens, stoves, computers, etc.) can be energy efficient (WSU 2003). Energy efficient appliances are widely spread in many countries and their cost is usually not significantly higher than the conventional ones. Most energy efficient appliances are much more beneficial than the conventional ones if life-cycle rather than only investment costs are considered (Ellis et al. 2007).

Energy efficient appliances are usually labeled, according to a certain labeling system (e.g. Energy Star), which provides information about appliances' energy performance and helps consumers make their choice.

## II.4 Main renewable energy supply options

In the previous section the main methods to reduce energy consumption of a building has been discussed. After these measures are implemented, in order to achieve the net zero energy status, the rest of the energy use should be covered by renewable energy.

As has been noted above, only on-site renewable energy supply options are considered in this dissertation. Table 7 presents the most common RES and respective technologies used in NZEBs, according to the literature.

Table 7. Main renewable energy sources and technologies used in NZEBs and their applications

| Renewable energy source | Technologies | Application in the building |
|---|---|---|
| **Solar thermal** | Flat plate collectors, evacuated tubes collectors, air collectors, combisystems | Space heating, space cooling, domestic hot water heating, ventilation air pre-heating, swimming pools heating |
| **Solar electricity** | Photovoltaics (PVs) | Lighting, appliances, electrical space cooling and heating, electrical cooking |
| **Wind** | Wind turbines (rural areas) | Lighting, appliances, electrical space cooling and heating, electrical cooking |
| **Geothermal** | Heat pumps | Space heating and domestic hot water heating, space cooling |
| **Biomass** | Biomass boilers (rural areas) | Space heating, domestic hot water heating |

**Source**: based on EST and Element Energy (2007)

### II.4.1 Solar energy

Being the main focus of this research, solar energy technologies are discussed in details in Chapter III, while other renewable energy options for buildings are briefly introduced below.

### II.4.2 Wind energy

Wind is used for electricity production by means of wind turbines, which convert the kinetic energy of moving air into useful mechanical power (Scottish Government 2009).

As was outlined above, before implementing any renewable supply solutions (including wind turbines), energy demand of a building should be reduced through energy efficiency improvement. Mithraratne (2009) also points out the priority of energy efficiency improvement. The author states that if the electricity demand in a building is reduced through energy efficiency measures, wind turbines could cover a significant share of energy consumption, especially in combination with solar thermal and PV applications.

There are three types of wind turbines depending on their size (see Table 8).

Table 8. The classification system for wind turbines

| Scale | Rotor diameter | Power rating | Scale of application |
|---|---|---|---|
| **Micro** | Less than 3 m | 50W – 2 kW | Residential |
| **Small** | 3 – 12 m | 2 – 40 kW | |
| **Medium** | 12 – 45 m | 40 – 999kW | Utility and industrial |
| **Large** | 46 m and larger | More than 1MW | Utility |

**Source**: Spera (1994) and Gipe (1999) in The Schumacher Centre for Technology & Development (2001); Global Energy Concepts (2005)

As can be seen from Table 8 for supplying electricity to residential, commercial and public buildings small and micro turbines are usually used (Global Energy Concepts 2005).

Cace et al. (2007) defines small wind turbines as "turbines that are specially designed for built environment, and can be located on buildings or on the ground next to buildings". According to the authors, the capacity of these wind turbines is usually between 1 and 20 kW. Therefore, such small wind turbines are the main focus of this section.

The amount of electricity produced by a turbine and it economic feasibility depends greatly on the wind speed (Syngellakis and Robinson 2006). According to Cace et al. (2007) and Mithraratne (2009), the annual mean wind speed should not be less than 5.5 m/s and not less than 5 m/s, according to EST (2009). According to Global Energy Concepts (2005), most wind turbines start to produce power when wind speed is 4 m/s and stop at 25 m/s. Estimates of energy output are usually based on annual mean wind speed. However, such aggregation may lead to inaccuracies and overestimation of potential electricity production (Syngellakis and Robinson 2006). The second important factor, which influences electricity production, is the rotor swept area (Scottish Government 2009).

There are several ways to analyze the performance of wind turbines. The first one is a load factor as “a percentage of the actual output of a turbine at a specific site compared with its maximum rated output” (EST 2009). It might be also called a capacity factor. “Capacity factor is the measured energy output as a percentage of the theoretical maximum rated output” (Mithraratne 2009). The second indicator is the coefficient of performance (COP), which is “the proportion of the energy in the moving air that a particular turbine can extract” (Scottish Government 2009). The third indicator for the performance evaluation is annual energy production (AEP). It estimates a turbine’s annual yield at an average wind speed of 5 m/s. The fourth indicator is a power curve, which presents power turbine’s output as a function of wind’s speed (EST 2009). Power curve is unique for each turbine and even site-specific conditions (Global Energy Concepts 2005). Therefore, it might be difficult to compare the performance of different turbines as manufactures may use different calculation methods and different wind speeds.

There are two main types of small wind turbines: horizontal axis and vertical axis wind turbines (HAWTs and VAWTs, respectively). The rotor blades of HAWTs move perpendicular to the ground; on the contrary, the VAWT’s blades move parallel to the ground (Scottish Government 2009).

HAWTs are also known as propeller-type turbines. In this type of a turbine a propeller-like rotor is mounted on a horizontal mast or tower. For turbines over 1 kW, tower are usually 12 - 36 m high. Rotor diameters vary from 1.1 to 15 m (Global Energy Concepts 2005). The rotor is very sensitive to the change in the wind's speed and turbulence; therefore, in order to maximize electrical output, it should be placed into the wind direction. It might reduce the performance and make the operation of the system more difficult due to repositioning. The choice of the location for such a turbine is also limited as it should be open areas with smooth air flow and few obstacles, which may be hard to achieve in urban environment (Cace et al. 2007).

On the contrary, VAWTs do not require repositioning due to yaw motor and are able to achieve appropriate performance with any wind directions. However, according to (Cace et al. 2007), the efficiency of VAWTs is usually lower than that of HATWs. They also state that wind turbines in urban areas can be performed in different shapes and sizes (e.g. energy ball or wind wall), which are most efficient in these particular conditions and location.

Depending on their location on-site, the turbines can be ground-based (or stand-alone) or building-mounted (Syngellakis and Robinson 2006). The first type requires a sufficient space on the building site, which might be unavailable in the urban conditions. Moreover, the wind's behavior is different in a built-up area and around a detached house (Heath and Walshe 2007). The second type requires an appropriate construction of the building and a roof, which can bear the weight and vibration. Usually, the turbines mounted on the roofs have not very high capacity – up to 1.5 kW (Mithraratne 2009). As for the performance, it is generally higher for stand-alone turbines than for building-mounted (load factor = 17-19% vs. 10%, according to (EST 2009). Scottish Government (2009) presents the same conclusion, giving 7% load factor for a building mounted turbine versus 30% for a stand-alone one. According to the monitoring results of existing turbines presented in EST (2009), some building-mounted turbines presented themselves as net consumers of electricity due to the inverter taking its power from the grid when a turbine was not generating.

As PVs, wind turbines can be connected to the electricity grid or not. In the first case, they can supply the excess electricity to the grid and consume it when the wind energy production is not sufficient. In the second case, this role should be played by batteries. Wind turbines usually also need the inverter for the same reasons as for PVs.

There are certain recommendations regarding installation of the turbine, such as:

- The mast or building roof should be approximately 50% taller than the surrounding objects;
- The turbines should be positioned near the centre of the roof;
- The turbine should be positioned on the side of the most common wind direction;
- The lowest position of the rotor has to be above the roof by at least 30% of the building height;
- Energy efficiency measures should be implemented before deploying a wind turbine(s) (Cace et al. 2007)

During the installation of a wind turbine the effects, which it has on environment should be taken into account as well. These include visual, noise, vibration and ecological impacts. The visual effects are closely related to the size of the turbine and its distance from the building. Subjectively, wind turbine might have negative effects on the landscape from esthetical point of view. It is usually related to their size and proximity to the building (Scottish Government 2009). Most of the wind turbines produce certain level of noise due to the work of the rotor, which increases with higher wind speeds. Turbines can also emit vibration to the ground (in case of ground-based systems) or supporting structures (in case of stand-alone turbines). Vibration can be avoided through good design and anti-vibration mounts. The most well-known turbines' negative impact on the environment is increase in bird mortality and distraction of their migration routes (Scottish Government 2009). This effect, however, is questionable. BWEA (2010) states that it is unlikely that wind turbines cause bird mortality. However, these possible negative effects should be taken into account during the planning, design and construction of windmills.

### II.4.3 Geothermal energy

Geothermal energy application in buildings usually means utilization of the difference between underground temperature and air temperature above the ground for heating in winter and cooling in summer. Ground is a massive heat storage, which has a low thermal conductivity (i.e. its temperature changes very slowly), and, therefore, is able to store the heat absorbed in summer till colder seasons, when it can be used for heating the building. Naturally warm earth and water below the surface provide a sufficient amount of renewable energy, which can be used during the whole year (RETScreen 2005b).

The amount of heat, which can be derived from the ground, depends greatly on the soil type and its thermal conductivity[11] (Groenholland UK Ltd 2007, Witte, van Gelder, and Spitler 2002). Soil conductivity is estimated to vary between 1.19 W/mK and 3.40 W/mK, depending on the soil profile, local conditions, measurement method (Witte, van Gelder, and Spitler 2002), as well as moisture content, dry density, mineral composition and temperature (Becker, Misra, and Fricke 1992). The higher thermal conductivity of the soil, the higher is the heat transfer (i.e. the



[11] Thermal conductivity is "a measure of the ability of a material to transfer heat" (Houghton Mifflin Company 2005) or "a measure of the ability of a substance to conduct heat, determined by the rate of heat flow normally through an area in the substance divided by the area and by minus the component of the temperature gradient in the direction of flow: measured in watts per meter per Kelvin" (Collins 2003).

soil easier absorbs and transmits the heat) and, therefore, the more favorable conditions are to supply the heat to a building.

In order to provide the underground heat for the consumption in a building, it needs to be converted into useful energy and delivered to the building. The most efficient way to do so is to use the ground-source heat pumps (GSHPs). A heat pump takes a low level heat from a large ground area (1.5 to 2 times the floor area of the building) and concentrates it, turning it into a considerable amount of high temperature heat, which is supplied to the building (NEP 2005).

Heat pumps consume electricity for the operation, however, these systems, especially GSHPs, have high energy efficiency (200-500%), as they produce more energy than they consume (RETScreen 2005b). In average, with 1 kWh of electricity consumed by a heat pump, it supplies the building with 3-4 kWh of useful heat. The relationship between the quantity of heat produced or removed and the amount of electricity consumed by the compressor of the pump determines the coefficient of performance (COP) (NEP 2005).

The utilization of heat pumps is recommended for NZEBs in a number of studies, such as Deng, Dalibard, et al. (2011), Deng, Dai, et al. (2011), Charron and Athienitis (2006), Biaou and Bernier (2008), Bojic et al. (2011), Groenholland UK Ltd (2007), etc.

A GSHP system has three major components:

- a heat pump;
- an earth connection;
- an interior heating or cooling distribution system (RETScreen 2005b).

The main role of the heat pump is to transfer the heat between the heating/cooling distribution system and the earth connection. The most common types of heat pump are “water-to-air” or “water-to-water”, which means that water or a water/antifreeze mix carries the heat to and from the earth connection and heats up or cools down the water or air circulated in the heat distribution system inside the building. There are several stages of GSHP work, which are the following in case of space heating:

- heat from the earth connection arrives at a heat exchanger (evaporator), through which it transfers to the cold liquid refrigerant and makes it evaporate;
- gaseous, low pressure and low temperature refrigerant passes into an electrically-driven compressor, which raises the refrigerant's pressure and temperature;
- high temperature, high pressure, gaseous refrigerant moves from the compressor into condenser, where it transfers the heat to the substance (air or water), which circulates in the building and heats it up;
- substance passes through an expansion valve, which reduces its pressure and temperature;
- cooled down substance flows to the evaporator, and the cycle starts again (RETScreen 2005b).

The same heat pump can be run for cooling. In this case the first heat exchanger becomes the condenser, and the second one becomes the evaporator. In this case it is called a reversible heat pump (NEP 2005). There are several types of the GSHPs depending on their earth connection system (see Table 9).

The key function of a heating/cooling distribution system is to deliver heating or cooling energy from the heat pump to the building. If the heat transfer substance is the air, then the distribution system is usually presented by an air duct system; if water is used for the heat transfer, the most common is a water loop system, which heat or cool floors and ceilings (RETScreen 2005b).

Table 9. Types of heat pumps depending on the earth connection system

| Name of the system | Abbreviation | Earth connection system | Technological requirements |
|---|---|---|---|
| **Ground-Coupled Heat Pump** | GCHP | uses the ground as a heat source and sink, with vertical ground heat exchangers | The boreholes, 45 - 150 m in depth with 1 or 2 loops of pipe with a U-bend at the bottom; connection to horizontal underground supply and return header pipes |
| | | uses the ground as a heat source and sink, with horizontal ground heat exchangers | Excavating and trenching equipment; a lot of land for excavation; a series of pipes laid out in trenches, 1-2 m below the surface |
| **Groundwater Heat Pump** | GWHP | uses the underground water as a heat source and sink | Water wells; sufficient ground water availability |
| **Surface Water Heat Pump** | SWHP | utilizes surface water bodies (lakes, ponds, etc.) as a heat source and sink | A series of coiled pipes submerged below the surface of a lake or pond as the heat exchanger |
| **Ground Frost Heat Pump** | GFHP | maintains sound structural fill in natural permafrost around foundations by extracting heat from the fill | Permafrost; earth connection is buried in the fill below the foundation; premium quality hermetic piping; good insulation between the frozen gravel pad and the foundation slab |

**Source**: RETScreen (2005b)

GSHP can be also utilized for domestic water heating. For this purpose the heat pump needs to be attached to a heat exchanger in the hot water tank. However, GSHP usually can only preheat water and the hot water tank must be equipped with an additional heat source to heat the water up to a temperature higher than 60°C at least once per day. GSHPs generally heat water up to a maximum of 50-55°C (NEP 2005).

### II.4.4 Biomass

Biomass is the organic matter, produced by photosynthesis that exists on the earth's surface. Biomass is the energy storage for the energy of the sun, which can be released through certain chemical processes (Schumacher Centre for Technology and Development 2005).

As presented in Table 7, biomass in the buildings is usually used for space and water heating by means of biomass boilers. Generally, the biomass heating system consists of the following parts:

- Biomass boiler;
- Fuel storage;

- Chimney;
- Hydronic distribution system for the hot water;
- Hydronic heat discharge system for space heating;
- A central control device with an outdoor temperature sensor (Egger et al. 2011).

The fuel is transported from the storage to the boiler where it is ignited and combusted. A boiler is highly insulated in order to minimize heat losses. The flue gas from the combustion process passes through a heat exchanger and transfers its heat to the water. The heated water is circulated through a hydronic distribution system by a heat pump (Egger et al. 2011).

RETScreen (2005c) provides more extended version of the process of heat production from biomass:

> **Biomass Fuel (Feedstock) Delivery:** if not available on site, the biomass fuel is delivered to a fuel receiving area, which must be large enough to accommodate the delivery vehicles.
>
> **Biomass Fuel (Feedstock) Storage:** the biomass fuel in the storage area must be sufficient to fire the plant over the longest interval between deliveries. The fuel can be stored in an outdoor pile, a protective shed, or inside a bin or silo. Outdoor storage, though inexpensive, permits precipitation and dirt to contaminate feedstock.
>
> **Biomass Fuel (Feedstock) Reclaim:** this refers to the movement of the biomass fuel from storage to the combustion chamber. It can be effected manually, as in the loading of outdoor furnaces with cut logs; fully automated, using augers or conveyors; or rely on both operator and machinery.
>
> **Biomass Fuel (Feedstock) Transfer:** this is the movement of the biomass fuel into the combustion chamber. In automated systems, a screw auger or similar device moves the biomass fuel and a metering bin measures the flow into the combustion chamber.
>
> **Combustion Chamber:** the biomass fuel is injected into an enclosed combustion chamber, where it burns under controlled conditions. To this end, a control system regulates the inflow of air in response to heat demand; in automated systems, biomass fuel flow is also regulated. Refractory materials keep the heat of combustion inside the chamber.
>
> **Heat Exchanger:** the heat from combustion is transferred to the heat distribution system via a heat exchanger.
>
> **Ash Removal and Storage:** this involves cleaning the system of bottom ash, which remains in the combustion chamber, and fly ash, which is transported by the exhaust gases. Bottom ash may

be removed manually or automatically, depending on the system. Fly ash may deposit in the secondary combustion chamber or the heat exchanger (necessitating cleaning), escape out the flue, or be taken out of suspension by a collection device (exhaust scrubber).

**Exhaust System and Stack:** this vents the spent combustion gases to the atmosphere. Small systems use the natural draft resulting from the buoyancy of the warm exhaust; larger systems rely on the fans feeding air into the combustion chamber to push out the exhaust gases, or draw the exhaust gases out with a fan at the base of the chimney (RETScreen 2005c)

In many cases a biomass system also includes an accumulator tank for heat storage. It is usually used if a biomass system is utilized for water heating. The tank is well-insulated and supplied by the water from the boiler on the top. Its design usually allows for water stratification. Using the accumulator tank compensates seasonal differences in energy demand, which allows for reducing the size of boiler, as the peak demand can be met by utilization of the tank and, therefore, there is no need to size the boiler to meet the peak demand, which is usually not cost-effective. Another option to deal with variations in heat demand is multi-boiler cascade system with two or more separate biomass boilers. When there is heating demand (for space or water heating) the first boiler starts operating at the most efficient level. If produced heat is not sufficient for covering the demand, the second boiler begins to work at the optimal level and so on. It allows the whole system to operate at the most efficient level (Egger et al. 2011).

There are three main types of the fuel for biomass heating systems (BHS): pellets, wood chips and firewood. Depending on the fuel type each system has its own design and technological features. The main features for each type of the system are presented in Table 10. The table illustrates that different BHSs can be applied in different types of buildings.

Table 10 provides more detailed information on the relation between the type of a BHS and building type. Generally, firewood BHSs are more appropriate for single-family houses especially in rural areas; wood chip BHSs suit better to large, usually commercial and public, buildings; and pellet BHSs may be utilized in most of the building types.

In order to minimize emissions from biomass combustion a two-stage combustion process is used in modern BHSs. It allows for maximizing the fuel combustion and, therefore, reducing the emissions due to the absence of unburned hydrocarbons in the flue gas. The efficiency of biomass heating systems has increased from 55 to more than 90% during the last three decades with simultaneous decrease in carbon monoxide emissions from 15000 to less than 50 mg/m$^3$ (Egger et al. 2011). These data show that modern BHSs are highly efficient applications, which can be used in NZEBs.

Table 10. Characteristics of different biomass heating systems (BHS) types

| BHS type | BHS application | BHS location | Fuel storage | Characteristics of the fuel | HV[12] | Average annual fuel demand of BHS |
|---|---|---|---|---|---|---|
| **Pellet HS** | Residential buildings | Special boiler room in the basement or heating containers outside the house | Dry and ventilated inside storage rooms close to boiler rooms; textile or steel tanks; integrated into HS containers; underground tanks | Clean and $CO_2$-neutral fuel produced from sawdust and wood shavings; length | 16.5 – 22.8 MJ/kg | 3-6 tones |
| **Wood chip HS** | Non-residential buildings or large residential in rural areas | Basement, free-standing heating containers, separate building | Inside storage rooms close to boiler rooms; outside storage | Clean and $CO_2$-neutral; require more storage, operations and maintenance than pellets | 14.4 MJ/kg for 25% water content[13] | 50 tonnes |
| **Modern firewood HS** | Residential buildings in rural areas | | Inside storage rooms close to boiler rooms; outside storage | Hot and fast combustion, available local wood resources, short transportation routes , water tank | Average11.3 for 15-60% water content | |

**Source**: based on Egger et al. (2011), Leaver (2000)



[12] Heating value (HV) is the amount of the heat released (in MJ or kWh) during the combustion of 1 kg of wood pellets

[13] Water or moisture content can be defined on a wet sample basis: the water content is a percentage of the original sample mass; or on a dry sample basis as a percentage of the dry fibre mass. Consequently, in woodfuel (on the wet sample basis), moisture content varies from a maximum of about 60% (freshly harvested) to 0% (oven-dried). In forestry industry the dry sample approach is usually used, therefore, the maximum moisture content would be about 150% (equivalent to 60% on the wet sample basis) (Yorwoods 2008).

Table 11. Choice of biomass heating systems for different building types

| Building type | Firewood boiler | Pellet boiler | Wood chip boiler |
|---|---|---|---|
| Domestic | | | |
| **3 bed semi (<20kW)** | √ | √ | |
| **4 bed detached (<30kW)** | √ | √ | |
| **Large farmhouse (<50kW)** | √ | √ | √ |
| School | | | |
| **Primary (<150kW)** | | √ | √ |
| **Secondary ( up to 1MW)** | | √ | √ |
| Community facilities | | | |
| **Village hall (<50kW)** | | √ | √ |
| **Visitors centre (<50kW)** | | √ | √ |
| Country estates | | | |
| **House + buildings (<500kW)** | | √ | √ |
| Local authority | | | |
| **Social housing block (250 units) (<500kW)** | | √ | √ |

**Source**: adapted from (South Wood Fuel Advice Service 2006)

This section has discussed the main options for renewable energy supply, which can be used in buildings, in general, and in net zero energy buildings, particularly. However, reaching a NZE goal usually requires implementing of a certain technological mix sometimes with a combination of several renewable supply options. The universal technological mix, which guarantees the achievement of NZE status, does not exist. It depends greatly on local conditions and design interests. Therefore, the possible technological mixes vary greatly from building to building. The following section provides the overview of NZEB case studies available from the literature, which may give the understanding of possible technological combinations, utilized in NZEBs.

## II.5 NZEBs case studies

This section presents the examples of NZEBs considered in the literature. For illustration purposes the information about case studies is presented in Table 12. The main features of selected NZEBs correspond to those discussed in the previous sections and include: building type, energy efficiency measures, renewable energy supply technologies, connection to the energy infrastructure, indicator of the balance, period of the balance, and purpose of energy use. The table also provides the information on the building's location, net zero energy balance and source of information for each case study.

The review of case studies is made with the purpose to see how NZEB concept is applied in practice and what strategies implemented in buildings help to achieve NZE in reality as well as their economic feasibility in terms of costs. The studies cited in the table include both the monitoring of existing NZEBs and simulation of possible NZEBs with special modeling tools. In this regard, the column with references also provides the information on whether the information is given for an existing building (*real*) or for a hypothetical one (*modeled*).

As presented in Table 12, NZEBs can take different forms. NZE status can be achieved in different building types and locations, through various technological mixes. One common feature for most of the NZEBs presented in the table is the improved energy efficiency of buildings, which proves its necessity in practice. The other feature is related to the utilization of solar energy as one of the most common renewable energy supply options. Most of the cases have one or another type of solar installations: PV or solar thermal collectors or both, while other supply options take place more rarely. It gives the ground for the assumption that solar energy is the most applicable energy source for NZEBs. However, in most of the cases solar energy does not cover 100% of energy consumption, therefore, the additional energy sources are needed. The NZEBs considered are usually connected to the electricity grid, with some exemptions, which gives the opportunity to use the grid as an auxiliary energy source, when the building's energy demand is higher than renewable energy supply, and as energy storage in the opposite situation.

It also stands for higher feasibility of grid-connected NZEBs as they do not require additional investments into batteries and oversizing renewable energy supply technologies.

Most of the studies calculate energy balance on the annual basis, but some of them also provide a monthly analysis. Very often the monthly analysis shows that a building is not NZE during some months, but can achieve NZE status at the end of the year.

NZEBs differ in their energy balances. The amount of energy consumed depends greatly on the building's size, location and, therefore, climate conditions, as well as energy efficiency measures. Energy production depends on the performance of renewable energy supply systems, which is to a great extent determined by local climate conditions and availability of required natural resources. Most of the studies presented show that net zero energy balance is achieved or is possible to be achieved. However, there are some cases, in which annual energy consumption of a building exceeds its energy generation, but a building is still positioned as ZEB.

Interestingly, some NZEBs allow for using fossil fuels (usually natural gas) if the consumed amount is covered by produced renewable energy on the annual basis. Such an approach is controversial. The energy can be supplied from a NZEB to the energy infrastructure in the form of electricity; therefore, it is widely believed that NZEBs can take only electrical energy from there (Norton and Christensen 2006). In case of the natural gas the situation is different as different types of energy are produced and consumed by the building.

Table 12. Selected case studies of NZEBs

| Location | Building type | Climate zones[14] | Energy efficiency measures | Energy supply technologies | Grid-connected | Balance indicator | Balance period | Purpose of energy use | Net zero energy balance | Reference |
|---|---|---|---|---|---|---|---|---|---|---|
| **South-east Queensland, Australia** | SF | Am | CFLs, LEDs bulbs; energy efficient appliances, minimization of pipe runs, high insulation, natural ventilation | Flat plate solar water heater, 1.7 kW monocrystalline PV system | no | primary energy | year + each month | Heating, lighting, appliances, hot water, cooking | total energy consumption (gas and electric) = 1.8MWh; total renewable energy electricity generation = 2.77 MWh. | (W. Miller and Buys 2010) *real* |
| **Toronto, Canada** | SF | Dfa | Energy efficient appliances, CFL bulbs, triple glazed south-facing windows, low flow showerheads, programmable thermostat | 33.5 square meters 5.89kWp PV system | not specified | n/a | year | Heating, cooling, lighting, appliances, hot water, cooking | Total annual electricity consumption = 6960.51 kWh. PV should cover it | (Tse and Fung 2007) *modeled* |
| **Lakeland, Florida, US** | SF | Cfa | 3-foot roof overhang, reflective white-tile roof, improved exterior insulation (R-10 value), advanced solar control windows, interior mounted, oversized ducts, high-efficiency appliances and lighting, a programmable thermostat | 2-kW solar water heater 4-kW utility-interactive PV system | yes | n/a, presumably final energy | year | Cooling, water heating | Solar technology system offsets about 85% of all grid electricity needs | (Parker, Thomas, and Merrigan 2001) *real* |
| **Japan, Hokkaido** | SF | Dfb | Superisulation and airtightness, double-glazed argon-filled windows with low-emissive coating, awnings for solar shading, direct solar heat gain, natural ventilation, phase change materials (PCM) for reducing heat load and overheating | grid-connected PV system: 3.1 kW crystiline silicon modules + 1.3 amorphous silicon modeules, ground source heat pump with earth heat exchangers, flate plate solar collectors | yes | n/a, presumably final energy | year | Heating, cooling, lighting, appliances, hot water, cooking | The total amount of annual energy use = 12.17 MWh. Approximately 91% is covered by RES technologies. Total purchased secondary energy = 1.14 MWh | (Hamada, et al. 2000), (Hamada, et al. 2001) *real* |
| **Central Asia** | SF | Csa/Csb | natural ventilation, The shape induces a "dome chilling effect", daylighting, additional covers in winter, chimney for the hearth fire, positioned directly below the roof opening | not specified | no | n/a | n/a | Electricity, water consumption, sewage | not specified | (Mrkonjic 2006) *real* |

14 Climate zones are specified according to Köppen–Geiger climate classification system (Kottek et al. 2006)

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **not specified** | not specifie d presum ably SF | n/a | CO2 Rankine cycle expander/compressor | The geoexchange (ground-coupled heat pumps), solar thermal combined heat and power (CHP), low exergy cooling and heating of buildings | yes | n/a | n/a | Space heating and cooling, hot water, electricity for equipment and appliances, refrigerators | not specified | (Platell, and Dudzik 2007) *real* |
| **Osijek, Croatia** | MF + C&P | Dfb | South orientation of the building, closed north wall, passive solar heating with stones heat storage, improved insulation of walls, facade and roof, efficient windows, floor heating | 24 m2 of solar collectors with tank of capacity of 1500 liters and PV panels of sufficient power for heating system and lighting, air-air and air-water heat pumps, 3.6 kW PV system; water electrolisis and extraction of hydrogen are under experiment | no | n/a | year | Heating, cooling, electricity, other is not specified | not specified, NZE status is only planned to be achieved | (Pichler 2009) |
| **The Netherlands** | SF | Cfb | South facing windows, shading in summer, direct cooling ventilation, advanced insulation of wall, roofs, floors, low emissivity double glazing, heat recovery, passive solar design, thermal mass use, energy efficient cooking, lighting and appliances | Solar water heater, possible contribution to space heating if a large storage is applied, polycrystalline PV, electrical heat pump | yes | n/a,, presumabl y final energy | year | Heating, electricity, hot water, cooking, appliances, lighting | Total energy demand (heat, electricity, heat pump) = 6.16 MWh; Total energy supply (PV, solar collectors, heat pump) = 6.23 MWh | (Gilijams e 1995) |
| **The Netherlands, Woubrugge** | SF | Cfb | 200 mm-thick foam glass Insulation, low-energy-transmission glazing, switches of electrical equipment; a sun lounge for passive solar heat; efficient lighting; a wood stove | 3.4 kWp in photovoltaic cells (76 modules of 45 Wp each,), and a 12 m2 active (thermal) solar collector, 1.6 m3 hot water tank | yes | n/a, presumabl y final energy | year | Heating, electricity, hot water, cooking, appliances, lighting | Total energy demand (gas, wood, collectors, electricity) = 9.41 MWh; Total energy supply (PV, solar collectors) = 10.08 MWh | (IEA/OE CD 1995) |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **The ÉcoTerra house, Eastman, Canada** | SF | Dfb | Air-tight construction, the continuous balanced mechanical ventilation with heat recovery ventilator (HRV), foam insulation, concrete floor mass, additional thermal mass in basement and ground floors, sun-shading overhangs, motorised blinds, broad leafs shading | Building integrated photovoltaic systems, two-stage geothermal heat pump (GHP) with environmentally-friendly refrigerant, 'net metering'[15] | yes | n/a, presumably final energy | year | Space heating, domestic hot water, lighting, appliances, electrical equipment, mechanical ventilation | annual PV electricity generation = 3.42 MWh; annual net energy consumption = 2.15 MWh. NZE status may be achieved with net-metering | (Noguchi et al. 2008) |
| **Las Vegas, US** | SF | Bwh | Advanced insulation, roof-mounted radiant barrier, thermal mass walls, an evaporatively-cooled condenser | Roof-integrated photovoltaic system, 2.3 $m^2$ solar water heater | yes | n/a, presumably final energy | year | Hot water, space heating and cooling | Annual PV production = 13.22 MWh, zero electricity consumption | (Zhu et al. 2009) *real + modeled* |
| **St John's, Newfoundland, Canada** | SF | Dfb | not specified | A 10 kW wind turbine | yes | Primary energy | year + each month | Space and water heating, cooking, lighting and electrical appliances | Annual energy production = 21.77 MWh; annual excess energy = 0.13 MWh | (Iqbal 2004) *real* |
| **Cardiff, UK** | SF | Cfb | double glazing with low E coating, suspended plaster board, ceiling, insulation, reflective foil, air gap, underfloor heating system, heat pump system | Solar domestic hot water (SDHW) systems, renewable electricity system (PV and small wind turbines), inverters for PV and wind turbine | yes | n/a | year | lighting, appliance, auxiliary heating for SDHW, floor heating system | Annual wind turbine and PV production = 7.31 MWh annual excess energy = 1.30 MWh | (L. Wang, Gwilliam, and Jones 2009) *real* |
| **Kragujevac, Serbia** | SF | Cfb | Advance insulation, double-glazed windows, water-to-water heat pumps and floor heating | 29 $m^2$ photovoltaics, solar thermal, ground heat exchanger | yes | n/a | year + each month | Space heating system, lighting and appliances, domestic hot water | Annual net energy consumption = 4.32 MWh; can be covered by PV generation | (Bojic et al. 2011) *modeled* |



[15] Net metering "enables the home occupants to receive credits for the excess electricity that is generated by the renewable energy sources installed on their house" (Noguchi et al. 2008)

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Denver, Colorado, US** | SF | BSk | Passive solar design, superinsulated envelope, double stud walls with fiberglass batt, increased glazing area on the long south side with double glazed, low emissivity, high solar heat gain coefficient glass and overhangs; balanced energy recovery ventilation system; CFLs; energy star appliances | Ground coupled heat pump (GCHP); 4kW photovoltaic system, point-source direct vent natural gas furnace, electric resistive heaters; solar water heating system with a natural gas tankless water heater as a backup | yes | n/a | year | Space heating, cooking, clothes drying, lighting, appliances, domestic hot water | Total annual energy consumption = 13.02 MWh; total energy production = 16.20 MWh; annual excess energy = 3.18 MWh | (Norton and Christensen 2006), (US DOE 2007) *real* |
| **Tennessee, US** | SF | Cfa | Polyester insulation; thermal distribution system, controlled mechanical supply ventilation; CFLs; heat recovery shower, insulated water pipes in the crawlspace, extended roof overhangs; energy star appliances; mechanical ventilation | 48-43W Amorphous Silicon PV Modules; heat pump, heat pump water heater | yes | n/a, presumably final energy | year + each month | Space heating, cooling, domestic hot water, other | Total annual energy consumption = 10.22 MWh; total energy production (PV) = 2.00 MWh; solar energy sold = 0.80 MWh | (Christian 2005) *real* |
| **Sendai, Japan** | SF | Cfa | Glass- wool insulation; fan coil units, thermopanels, double-pane windows with air layer, an airtight construction, ventilation heat recovery, energy-efficient lightings and appliances | 30.4 m2 liquid-type solar collector; 1.5 kW photovoltaic system; sky radiation cooling design; 600-W heat-pump with 1.6-m auxiliary tank | yes | Primary energy | year | Space heating, cooling, domestic hot water, lighting, appliances | Total annual energy consumption = 32.55 MWh, annual PV production = 1 MWh | (Saitoh and Fujino 2001) *modeled* |
| **Baraboo, WI, US, Aldo Leopold Legacy Center** | C&P | Dfb | Proper orientation, daylighting, natural ventilation, overhangs on south windows, highly efficient building envelope, greatly increased insulation, displacement ventilation, variable-frequency-drive fans, demand-controlled ventilation, water-efficient faucets, energy efficient lighting and appliances | Ground-source water-to-water heat pumps, earth-tube system, 39.6-kW photovoltaic array | yes | n/a, presumably final energy | year | Heating, cooling, lighting, fans/pumps, plug loads, equipment, vertical transport, domestic hot water | Annual energy demand = 54.23 MWh; annual PV production = 61.25 MWh ; Annual electricity sold = 34.34 vs. purchased = 26,18 MWh | (US DOE 2008) *real* |
| **Los Angeles, CA, US, Audubon Center at Debs Park** | C&P | Csb/Csa | Fluorescent T-8 lamps, Energy Star appliances, daylighting, operable windows for natural ventilation, efficient fans for mechanical ventilation, overhangs on south windows, high internal thermal mass | 25-kW PV system; 96 battery cells; a small generator is used to deep charge the batteries | no | n/a, presumably final energy | year | heating, cooling, lighting, office equipment | Annual energy demand = 25.23 MWh; annual PV and solar thermal production = 25.23 MWh ; | (US DOE 2008) *real* |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Los Angeles, CA, US, Challengers Tennis Club** | C&P | Csb/Csa | Natural ventilation, window shading in the summer and roof shading, ceiling fans, thermal mass in the floor and walls, a highly insulated building envelope and doors, double-glazed windows, high-efficiency equipment, daylighting, fluorescent lighting, motion sensors | Thin-film silicon PV array | yes | n/a, presumably final energy | year | Heating, cooling, lighting, fans/pumps, plug loads, equipment, vertical transport, domestic hot water, tennis court lighting | The solar PV system provides 100% of the annual electricity used at the site. Annual PV production = 9.41 MWh ; annual energy purchased = 0.10 MWh | (US DOE 2008) *real* |
| **Rohnert Park, CA, US, Environmental Technology Center at Sonoma State University** | C&P | Csb | Daylighting, operable windows, light colors for surfaces and finishes, high-efficacy T-5 fluorescent lamps, high-performance windows and doors, passive solar heating, sufficient sensors and control logic, thermostats with night setback | 3-kW roof-integrated photovoltaic system; high-efficiency, condensing oil or gas boilers and furnaces | yes | n/a, presumably final energy | year | Heating, cooling, lighting, plug loads, equipment, domestic hot water | The solar PV system provides 100% of the annual electricity used at the site. Annual PV production = 2.44 MWh ; annual energy purchased = 0.95 MWh | (US DOE 2008) *real* |
| **Kailua-Kona, HI, US, Hawaii Gateway Energy Center** | C&P | BSh | Daylighting, glare control, building proper orientation, photoelectric daylight sensors, occupancy sensors, good roof insulation, passive thermal chimneys | Building-integrated 20-kW photovoltaics | yes | n/a, presumably final energy | year | Heating, cooling, lighting, plug loads, equipment, domestic hot water | A net-exporter of electricity; the PV produces more energy than the building uses. Annual PV production = 32.90 MWh ; annual energy purchased = 3.65 MWh | (US DOE 2008) *real* |
| **San Jose, CA, US, IDeAs Z Squared Design Facility** | C&P | Csa | Daylighting, occupancy sensors, high efficiency office equipment, innovative automatic controls, radiant floor heating and cooling, highly rated insulation, monitoring equipment | 2,600 square feet roof membrane integrated PV system, a ground-source heat pump | yes | n/a, presumably final energy | year | Heating, cooling, lighting, plug loads, equipment, domestic hot water | PV to provide 100% of net energy use. Annual PV production = 56.50 MWh | (US DOE 2008) *real* |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Oberlin, OH, Oberlin College Lewis Center** | C&P | Dfa | Highly rated wall and roof insulation, daylighting, south-facing windows, proper building orientation, operable windows for natural ventilation, high internal thermal mass, light colors for surfaces and finishes, LEDs for lighting, high-performance windows and doors, air infiltration, lighting controls | 4,000 ft2 of monocrystalline PV panels on the south-facing roof, another 100 kW PV system over the parking lot adjacent; closed-loop geothermal wells; supplementary radiant coils | yes | n/a, presumably final energy | year | Heating, cooling, lighting, fans/pumps, plug loads, equipment, vertical transport, domestic hot water, HVAC | PVs produce more than 110% of annual electricity consumption. Annual PV production = 145 MWh ; annual energy purchased = 16.90 MWh | (US DOE 2008) *real* |
| **St. Paul, MN, US, Science House at the Science Museum of Minnesota** | C&P | Dfa | Passive solar design, daylighting, energy-efficient windows and doors, low-density foam wall insulation; low electric lighting wattages; automatic light controls, wall colors for high light reflective values; a carbon dioxide sensor in the ventilation system, multi-modal natural ventilation; continuous computer monitoring, total ventilation energy recovery. | High efficient ground-source heat pumps with a variable pumping loop; 8.8-kilowatt photovoltaic | yes | n/a, presumably final energy | year | Heating, cooling, lighting, fans/pumps, plug loads, equipment, domestic hot water | PV system produces more energy than the building uses. Annual PV production = 7.90 MWh; annual energy consumption = 5.71 MWh | (US DOE 2008) *real* |

**Notes**: SF – single-family; MF – multi-family; C&P – commercial and public

## II.6 Feasibility of NZEBs

The analysis of NZEBs economic feasibility is rather limited in the literature. Not all the studies presented in the Table 12 include the analysis of costs related to NZEBs. Therefore, in this section only some of them are discussed in order to give some ground for understanding of the potential for NZEBs' cost-effectiveness.

Miller and Buys (2010) show that the analyzed NZEB has exceeded the definition of a net zero cost house as the net cost for the provision of energy services for the household was a net income of $829 at the end of the year. For comparison the authors give the example of annual energy costs for an average Queensland household, which is 1600 USD. As another advantage of the NZEB, the authors point out that its annual energy costs are not affected by the change in electricity prices, which have the tendency to grow in Queensland. Unfortunately, the study does not provide the information on total construction costs for the NZEB and average Australian house, which would give the opportunity to conclude on the overall cost difference between the conventional house and a NZEB.

Saitoh et al. (2001) also compare annual energy costs (electricity, water, and city gas) for conventional and NZE buildings. The authors show that the costs are lower in case of the NZEB. The total annual energy costs in NZEB are only 15% of those in the conventional house. The authors state that the total investment cost for energy facilities, equipment and appliances was about 160,000 USD, which is 30% of the total construction costs (533,333 USD). The study, however, does not compare total construction costs of the NZEB with those of a similar conventional house.

Noguchi et al. (2008) demonstrate a considerable reduction in annual energy costs in the NZEB in comparison to a typical Quebec home – from 3200 USD to 260 USD or even zero if an additional annual credit is provided by the net metering. However, the study omits the analysis of the investment costs for NZEB, only mentioning that they are significant.

Parker, Thomas, and Merrigan (2001) present a rather limited cost analysis of NZEBs comparing the average monthly power costs of NZEB (27 USD) and a conventional building (147 USD). The authors state that "there are up-front costs incurred with purchasing the solar technology system and installing certain energy efficiency measures. But, in many cases, these costs can be recouped over time by the savings on the monthly energy bill". The more precise information on the total investment costs for the NZEB and the period, during which they can be covered, is not available in this study.

Platell, and Dudzik (2007) say even less about NZEB's feasibility, stating, however, that the analyzed "ZEH employing the $CO_2$ Rankine cycle is expected to offer attractive cost benefits". "It is too early to draw final conclusions about the total system economics, but when several of the new component costs offset the cost of conventional components, there is a potential to offer an attractive payback period to the end user".

Tse and Fung (2007) present more advanced cost analysis for upgrading a single-family building to the NZE status. They have calculated the total upgrade costs as 107,760 USD. The authors have also provided the results for the calculation of the annual energy costs savings due to PV electricity production equal to 3490.2 USD. They have estimated the payback period[16] for the entire NZEB, including all the systems and improvements, as 31 years. The payback period may be reduced to 19 years in case the excess electricity produced by the PV is sold to the grid with the standard offer in Ontario of $0.42/kWh.

[16] Here the payback period is the period of time needed to cover the investment costs of the NZEB with energy cost savings resulted from reduction of the net energy consumption from the energy infrastructure.

IEA/OECD (1995), on the contrary, states that the payback period for the NZEB in the Netherlands is not realistic, as the investment costs for the PV are more than 64,000 US$ and annual income due to PV yield is only 405 US$ (which results in approximately 158 years of payback). However, this study emphasizes, that its main goal was to show the technical feasibility of NZE house, and predicts that “the required equipment will become cheaper and energy prices will rise to the point where the zero-energy concept becomes economically feasible”. It is worth to point out that the study is dated to 1995. There is a ground to assume that during 15 years the trends outlined by the authors have been taking place and NZEBs have become more economically feasible.

Christian (2005) does not provide the results for the payback period, but it can be easily calculated from the data presented. According to the measurements, the annual income generated through the solar system is 301 USD and the cost of the solar system is 22,388 USD. Therefore, the payback period for the solar system is 74 years (22,388 ÷ 301), which is not realistic as it is longer than a PV’s lifetime and even average building’s lifetime. Moreover, the energy cost savings produced by the PV do not cover the annual energy costs (644 USD). Total construction costs of the NZEB are 115,802, while it is only 73,795 for the “base” house. Taking into account that NZEB is 36% more expensive, such a house is not economically feasible. However, the author states that the building is experimental, which caused higher costs, and further research and development are leading to first cost reductions (Christian 2005). At the same time the calculated payback of the net total investment for efficiency and solar generation for Challengers Tennis Club in Los Angeles is very reasonable - 12 years (US DOE 2008).

Zhu et al. (2009) have calculated the payback period for different technologies used in the NZEB. The results show that most of the technologies can be paid back in short or medium term.

For high performance windows, the compact fluorescent lights, the air conditioner with a water-cooled condenser and the highly-insulated roof the payback period varies from 0.3 to 9.5 years. PV requires 26.4 years for the payback, while solar heater – 24.5. Only thermal mass walls demonstrate the unrealistic payback (more than 600 years), which means that this technology is too expensive at the moment in relation to provided cost benefits. The authors have not calculated the payback period for the NZEB itself, but provided the data on additional investment costs in comparison to “baseline” building. Total added investment costs for the NZEB are 98,253 USD. It seems to be high; however, the conclusion on feasibility cannot be made as the data on annual energy cost savings are not provided.

Iqbal (2004) also provides the data on cost of the technologies and installation for the NZEB in Newfoundland (the total costs are 44,000 USD), without presenting the results for energy cost savings. Bojic et al. (2011) have calculated the payback period only for the PV and demonstrate that it depends greatly on the level of feed-in tariffs: 18 years without feed-in tariffs for the cheapest PV in Serbia; with feed-in tariffs of 0.23 euro/kWh - the payback period is 9-20 years depending on the unit price of the PV array; and for feed-in tariffs of 0.6 euro/kWh it is only 3-7 years. It illustrates that policy support can make NZEBs much more affordable.

An interesting cost analysis is presented in Anderson, Christensen, and Horowitz (2006). The study analyzes the least-cost solution for NZEBs in five cities, belonged to different climate zones. Figure 1 illustrates the relation between costs and energy cost savings for different NZEBs. For all cases the costs are the lowest when energy savings are around 40% and they start to rapidly grow after 50%. Therefore, at 100% of energy savings, which corresponds to NZE status, the level of costs is very high, which might cause the doubts about NZEBs’ economic feasibility.

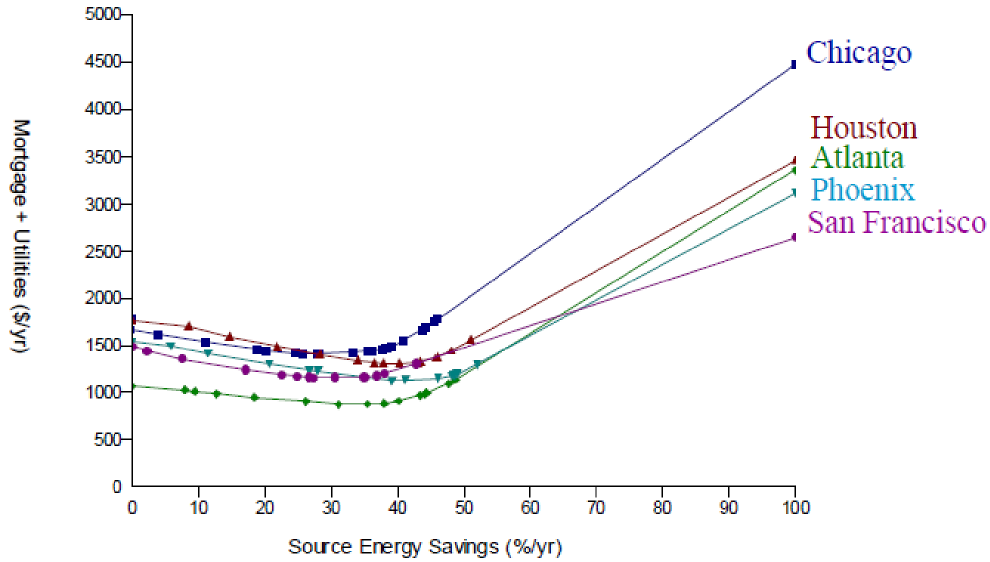



Figure 1. Least-cost curves for five cities

**Source**: Anderson, Christensen, and Horowitz (2006)

Therefore, the analysis of literature shows the lack of comprehensive economic feasibility analysis for NZEBs. There are certain data and estimations, which give the understanding that the feasibility depends greatly on the design and technological mix used in the building, on the one hand, and location and climate conditions, which determine energy needs, on the other. Therefore, it is difficult to conclude in what case NZEBs may be feasible or not only on the basis of the literature review. Consequently, a more comprehensive analysis is needed, which will take into account various factors.

## II.7 Summary

This literature review is aimed at discussing the main theoretical and practical aspects of net zero energy buildings (NZEBs). The main idea of NZEBs is that they consume not more energy than they produce renewable energy. The review has demonstrated that the achievement of the NZE status depends on the choice of the definition for a NZEB. Different types of such definitions have been discussed. They include different aspects depending on the building's functions, target audience, local conditions, design preferences, etc. Therefore, the same building can be NZE, according to one definition, and not to be, according to another.

Although there is a variety of approaches to define NZEBs with different features and peculiarities, they have a common requirement for achieving NZE goal: first of all, energy demand of the building needs to be reduced through energy efficiency improvement and, secondly, the remaining energy consumption should be covered by renewable energy.

This review considers different energy efficiency measures, which can be applied in NZEBs, starting with building orientation and design and finishing with utilization of energy efficient lighting and appliances. The main conclusion is that the complex of these measures can dramatically reduce energy demand.

Different renewable supply options are also discussed in order to provide the understanding of how renewable energy can be produced in different types of building under different conditions. The analyzed literature shows that the wide utilization of renewable energy technologies in buildings is usually aggravated by their dependency on climatic and weather conditions and, consequently, unstable performance, limited efficiency, high installation costs and lack of the support from the government. These barriers can be significantly reduced by certain policy instruments and incentives for renewable energy development, including R&D activities (however, it is not the subject of this dissertation).

The case study analysis presented in this dissertation has shown that NZEBs are technologically possible in different locations, climate conditions and building types. There are also different technological mixes, which enable the achievement of NZE goal. The most common are the solar applications (PVs and solar thermal collectors), which are used in most of the cases reviewed. However, very often these technologies are implemented with the combination of some other solutions (wind turbines, heat pumps, etc.).

As for economic feasibility of NZEBs, the results are controversial. There are some studies, which show that NZEBs can be feasible, while others present the results that investments in NZEBs cannot be paid back during realistic time. Therefore, this question requires a separate and deep research.

In general, the subject of NZEBs is becoming more and more acute nowadays, having both supporters and opponents, which makes it complex, challenging and very interesting for the research.

# III CHAPTER. SOLAR ENERGY TECHNOLOGIES USED IN (NZE) BUILDINGS

This chapter describes main types of solar technologies available nowadays on the market. Solar energy technologies can be divided into three main groups depending on the type of energy they produce (heat or electricity):

- Solar thermal technologies (see Section III.1);
- Solar electric technologies (see Section III.2);
- Hybrid solar PV/T technologies (see Section III.3).

Each of these categories is discussed in more details below.

## III.1 Solar thermal technologies

Technologies in this group are mainly represented by solar collectors – "a special kind of heat exchangers that transform solar radiation energy to internal energy of the transport medium" (Tyagi et.al. 2012). This energy in the form of heat can be used in buildings for heating space and domestic water and/or drive cooling devices.

Solar-thermal systems usually consists of several modules with collector units of around 2.5–10 $m^2$ surface, which can replace conventional roofing material and perform the insulation function for the roof (Eicker 2001).

The solar collector is designed in a way that allows it to capture solar radiation, convert it into heat, which is then transported by the fluid medium to the heat storage, from where hot water is taken for the building's use.

A typical solar system with a collector consists of several parts: an absorber, a heat-carrying pipe and a storage tank. The main function of the absorber is to capture the sunlight and transfer its heat to the fluid (usually a mixtures of water and antifreeze agents for cold climates) (Eicker 2001). For this purpose the absorber is usually covered with the glass, which transmits about 90% of shortwave solar radiation inside the collector and none of the longwave radiation emitted outward by the absorber (S. Kalogirou 2009). In this regard, a selective coating gives the opportunity to optimize the relation between absorbed and emitted heat and thereby increases thermal performance.

Heat-carrying pipes attached to or integrated in the absorber transfer the captured solar heat to the fluid. In order to reduce the heat loses during this process the insulation is applied to both the absorber and the pipes. The heated fluid is moved through the pipes to the storage tank and the heat is transferred to the tank through a heat exchanger in the lower part of the tank. The longer the pipes, the more heat losses take place during this transportation. In order to reduce them the distance between collector and the tank should be decreased (Fieber 2005).

The main role of the storage tank is to store the heat for the periods when the solar supply is limited (night, cloudy days). From the upper part of the tank the heat exchanger transfers the heat from the tank to the space heating or domestic hot water systems. As the upper and lower parts of the tank have different functions, there should be a respective stratification of the water temperature between them: the lower part is colder and the upper part is hotter. Moreover, the temperature in the upper part should be appropriate for the space or water heating requirements. If is lower, the auxiliary heating system, which oil, gas, electricity or biomass (probably, the most appropriate for a NZEB) is needed (Fieber 2005).

Ideally, solar collectors should be oriented towards the Equator. The optimum tilt angle of the collector equals the latitude of the location with variation of 10-15° depending on application. If the collector is used for space heating the optimal is the latitude plus 10°; for water heating - the latitude plus 5°; for space cooling - the latitude minus 10° (S. Kalogirou 2009).

There are two main groups of solar collectors: non-concentrating or stationary and concentrating. The main difference between them is that a non-concentrating collector has the same area for intercepting and absorbing solar radiation, whereas a sun-tracking concentrating solar collector usually has concave reflecting surfaces to intercept and focus the sun's beam radiation to a smaller receiving area, thereby increasing the radiation flux (Tyagi et.al.2012).

There are different types of solar collectors available on the market, which can be installed in individual buildings. This section will discuss the following types:

- Flat-plate collectors (see Subsection III.1.1);
- Evacuated-tube collectors (see Subsection III.1.2);
- Air collectors (see Subsection III.1.3);
- Concentrating collectors (see Subsection III.1.4);
- Combisystems (see Subsection III.1.5).

### III.1.1 Flat-plate collectors

The flat plate collectors are usually designed for operation under low (less than 60 ◦C) or medium temperature (60-100 ◦C). They are used to absorbed solar energy, convert it into heat and then to transfer that heat to stream of liquid or gases (Tyagi et.al. 2012).

Flat-plate collector is a usually flat box with glazing (glazed collectors) and good insulation. The glazing may have an antireflective coating in order to maximize the solar gain. The black color of absorbers maximizes the amount of captured radiation (Fieber 2005). There are also unglazed flat-plate collectors, which are used for heating the swimming pools. In this case the absorber is made of UV-resistant plastic ("rubber-like Ethylene Propylene Diene Monomer (EPDM) mat, metal, or extruded polypropylene plastic") (Baechler et al. 2007). The performance of this collector type is usually lower than that of the glazed collectors (Eicker 2001).

A typical flat-plate collector usually includes the following essential features:

- A flat blackened absorbing plate (normally metallic) upon which the solar radiation falls, gets absorbed and converted into thermal energy
- Tubes, channels or passages attached to the blackened absorber plates to circulate the fluid required to remove the thermal energy from the plate
- Insulation at the back and sides of the absorber plate to minimize conductive heat losses
- A transparent cover of glass or plastic to reduce the upward convection and radiation heat losses from the absorber plate
- A weather tight container, which encloses the above components (Tyagi et.al. 2012).

Flat-plate solar collectors are mainly used for domestic and industrial purposes. A typical flat-plate collector is presented in Figure 2.

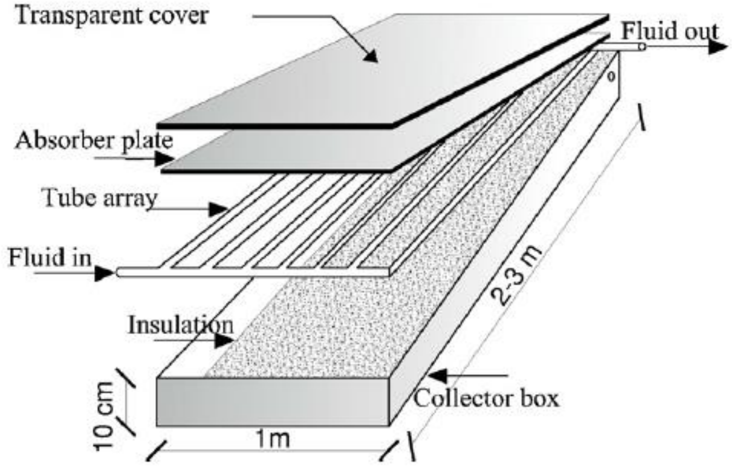



Figure 2. Schematic presentation of a typical flat-plate collector

Source: Tyagi et.al. (2012)

### III.1.2 Evacuated-tube collectors

In evacuated-tube collectors the absorber is presented by small diameter metal pipes inside evacuated tubes. Transparent cover of the absorber (usually with a selective coating) captures the solar radiation and traps it inside the collector. Moreover, the heat losses are considerably reduced by additional insulation provided by vacuum (Eicker 2001). Due to a highly selective surface coating and vacuum insulation of the absorber element collectors of this type can have high heat extraction efficiency compared with flat plate collectors in the temperature range above 80 ◦C (Tyagi et.al. 2012).

There are two main types of evacuated tube collector available on the market: direct-flow and heat-pipe collectors (AEE 2009).

The collectors of the first type consist of a group of glass tubes; inside each tube there is a flat or curved aluminium fin attached to a metal or glass absorber pipe. The fin is covered with a selective coating that absorbs solar radiation, which warms the heat transfer fluid (usually water).

There are usually two separate pipes, where the fluid circulates: one for inlet fluid and the other for outlet fluid (Darling 2004a).

The main difference between a direct flow tube and a heat pipe tube is that the heat carrier fluid inside of the copper heat pipe is not connected to the solar loop (AEE 2009).

Inside the heat pipes there is a special freezing-resistant fluid (usually of purified water and some special additives) that vaporizes, when the pipe is heated above an adjustable temperature. This vapour rises to the top of the heat pipe (condenser) transferring heat to the carrier fluid in the collector (AEE 2009). After giving up its heat, the condensed liquid then flows back into the base of the pipe (Baechler et al. 2007).

A typical evacuated tube collector is presented in Figure 3.

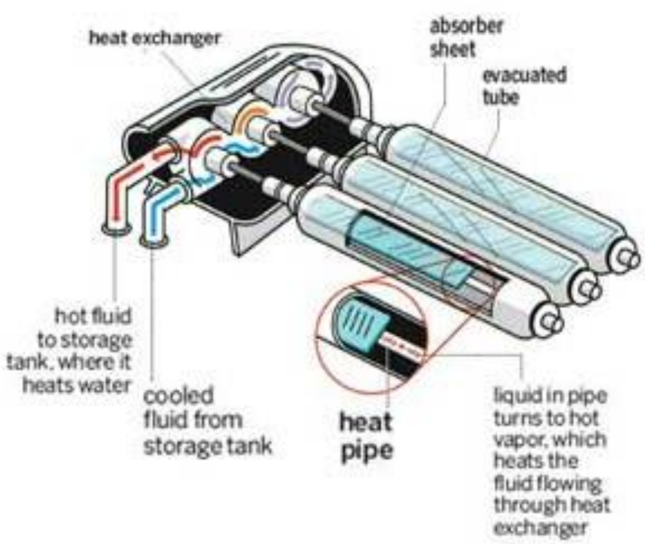



Figure 3. Schematic presentation of a typical evacuated tube collector

Source: Solar Tribune (2011)

Evacuated tubes have higher efficiency than other collectors in cloudy weather and tend to provide higher temperatures than flat plate collectors (Baechler et al. 2007). Menyharth (2009) supports this point of view by the results of the testing of two evacuated tube and two flat-plate collectors. However, Fieber (2005) refers to the research presented in Kovacs and Pettersson (2002) to claim that the evacuated tube collectors have lower performance in the cold weather due to the colder glass surface, which leads to the longer periods of ice, snow or frost cover. Kalogirou (2009) also states that the performance of evacuated tube collectors reduces greatly "when conditions become unfavorable during cold, cloudy, and windy days".

Mehalic (2009) points out that the efficiency of the collectors depends on the temperature difference between the inlet fluid and outside air: "collectors operate most efficiently when the temperature of the inlet fluid (Ti) is the same as or less than the ambient temperature (Ta) of the air". The author emphasizes that when this difference is increasing the decrease in efficiency for evacuated tube collectors is less steep in comparison to flat-plate collectors, which means that the former perform better in cold outside conditions (Mehalic 2009). Figure 4 shows the relation between the inlet and ambient temperature difference and efficiency of different collector types.

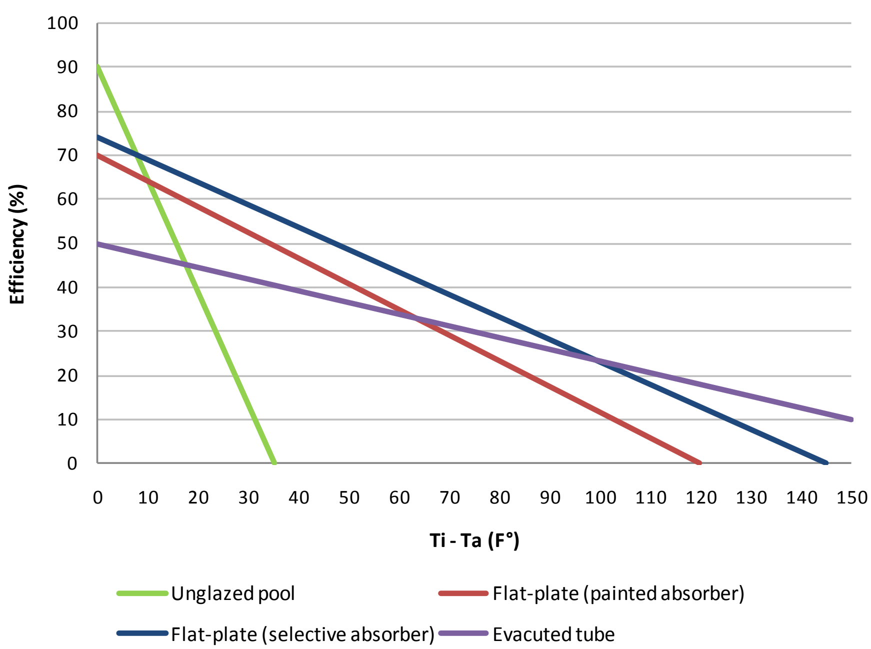



Figure 4. Efficiency of solar collectors

Source: adapted from Mehalic (2009)

It can be seen from Figure 4 that evacuated tube collectors (ETs) become more efficient than flat-plate collectors only when the temperature difference exceeds 90-100°F (32-38°C). According to Mehalic (2009), most of the systems do not experience such conditions. The author, however, concludes that "ET collectors are capable of producing higher temperatures overall and can produce more heat in cold weather. ETs also perform much better under cloudy and windy conditions, again a result of the improved insulation keeping more heat "in the collector" (Mehalic 2009). The author also claims that ETs work better if the higher temperature of the water is needed. At the same time Mehalic admits that the efficiency of ETs can be undermined in the condition with a lot of snow and heavy frost.

Menyharth (2009) has also investigated the performance of these types of collectors in different climate conditions and concluded that the flat-plate collectors performed best at moderate difference (about 80°F) between inlet and ambient temperatures, and when providing hot water temperatures to about 145°F. On the contrary, the evacuated tube collectors have a high performance under severe ambient temperatures (more than 100°F difference between inlet and ambient temperatures).

Another advantage of evacuated tubes is their less sensitivity to sun angle and orientation than flat-plate collectors: "some tubes can even be individually rotated within the rack system to favor late or early sun" (Mehalic 2009). Table 13 compares different characteristics of these two types of collectors.

Table 13. Comparison of the characteristics of flat-plate and evacuated-tube collectors

| Characteristics | Flat-plate collector | Evacuated tube collector |
|---|---|---|
| **Proven technology** | √ | √ |
| **Typically less expensive** | √ | |
| **Less affected by collector orientation** | | √ |
| **More efficient at high temperatures** | | √ |
| **More easily sheds snow** | √ | |
| **More efficient in cloudy weather** | | √ |
| **Suitable for drainback systems** | √ | |

Source: Mehalic (2009)

### III.1.3 Air collectors

Air collectors use air as a medium for heat transfer instead of liquid as in the types discussed earlier. The heat transferred by air-based solar collectors can be used for ventilation air heating, space heating, or crop drying and other drying applications. The air collectors usually weight less than liquid-based collectors, they do not experience problems with corrosion, liquid freezing or overheating, and they can be integrated into buildings. Among their disadvantage is low storage capacity (Darling 2004b). They also have lower efficiency due to low thermal capacity of air and low absorber-to-air heat transfer coefficient (Ion and Martins 2006).

Solar collectors, both liquid-based and air-based, can also supply heat for thermally driven cooling technologies, mainly absorption and adsorption coolers.

In absorption technology the refrigerant (water or ammonia) is absorbed in a liquid solvent (water–lithium bromide or water), desorbed by direct or indirect heating in a generator at high temperatures, and brought to the required condenser pressure. During absorption, solution heat is released, which must be removed via a cooling circuit. The drive temperatures for desorption are between 90 and 140°C, depending on the technology. In adsorption technology the refrigerant water is absorbed to a solid such as silica gel, with release of adsorption and condensation heat. The heat of adsorption tends towards zero, but the condensation heat has to be removed. The drive temperature for this technology is lower than for the absorption one - 60–70°C, so solar energy is more applicable. Absorption technologies can produce from 0.6-0.7 kW of cold per kW of assigned amount of heat up to 1.1–1.3, depending on the complexity of the technology. For adsorption technologies such a coefficient of performance (COP) varies from 0.5 to 1.0 (Eicker 2001; ESTIF 2006).

### III.1.4 Concentrating collectors

Concentrating collectors provide energy at temperatures higher than the types of collectors discussed previously. Concentrating collectors redirect solar radiation passing through an aperture into an absorber and optically concentrate solar energy before converting it into heat. Concentration is usually ensured by reflection or refraction of solar radiation by the use of mirrors or lens. A concentrating collector usually requires tracking of the sun (Tyagi et.al. 2012).

Concentrating collectors can be classified into non-imaging and imaging depending on whether the image of the sun is focused at the receiver or not. Compound parabolic concentrator (CPC) belongs to the first group, while the second group includes parabolic trough collector, linear Fresnel reflector, central receiver and parabolic dish (Tyagi et.al. 2012).

Concentrating collectors are rarely used in small-scale building-integrated installations, and are more applicable for industrial purposes, and, therefore, are not discussed in details here.

### III.1.5 Solar combisystems

A promising solution for both domestic water and space heating can be so-called "solar combisystems". In case of extremely well insulated houses and low-flow mechanical ventilation (which is required in ZNEBs), the solar contribution by combisystems can reach 100% of energy consumption for hot water and space heating (IEA 2002b). Combisystems have larger size of the collector area: 10-30 m2 instead of usual 4-8 m2 for domestic hot water application (Charron and Athienitis, 2006).

In a combisystem there are two main energy sources, which supply: the solar collectors when solar energy is available and the auxiliary energy source (oil, gas, wood, electricity, geothermal, etc.) when solar energy input is not sufficient. However, for NZEBs the choice of the auxiliary system is limited as it should be very energy efficient. Charron and Athienitis (2006) recommend using ground-source heat pumps as the auxiliary heating system in NZEBs.

The simultaneous heat supply for two end-uses requires different temperature of water in the storage tank. Of course, two separate storage tanks can be constructed for hot water and space heating; however, it will require more space, investments and system control (Charron and Athienitis, 2006). Therefore, the optimal solution may be a single tank with the vertical stratification, which means that colder water at the bottom of the tank is not mixing with the hotter water on the top of the tank (Charron and Athienitis, 2006; IEA 2002b).

The principle of the vertical stratification can be realized in the following way:

> Stratification can be built up by adding heat *(charging)* at the top of the store or by removing heat *(discharging)* from the lower part of the store. Charging or discharging can be achieved either directly via inlets/outlets where the water is injected/removed to/from the store, or indirectly via a heat exchanger placed inside the store and surrounded by store water (IEA 2002b).

Solar and auxiliary energy sources and different tubes from the tank are connected at different heights to avoid mixing, maintain the temperature layers and stratification in the tank (Charron and Athienitis, 2006). Utilization of one tank with the vertical stratification reduce the number of pipes needed, space requirements and system weight (Weiss 2003).

A promising option is utilization of solar combisystems to provide heat to Direct Solar Floor Heating (PSD) systems. This system does not require a water tank because it uses the building mass as storage for heat. It provides comfort to the occupants and maximizing the solar energy storage without generating excessive temperatures inside the building. However, in order to reach a high effectiveness, improved control/command strategies are needed (Papillon et al. 2007).

There are different types of solar combisystems. However, it is not the purpose of this paper to discuss all of them in details. Below (see Table 14) one possible classification of solar combisystems is presented elaborated by (IEA 2002b) on the basis of two features: (1) the method used for storing the heat produced for space heating by the solar collectors and (2) the management philosophy chosen for the heat produced by the auxiliary heater. Three optional features are also considered. A classification code is assigned to each feature (capital or small letters). Using the combination of these codes (e.g. AP, CMl, DSd, etc.) 21 different combisystems are discussed in (IEA 2002b).

One of the problems with solar combisystem is that they generate too much heat in summer. The heat needs to be discarded in order to avoid overheating in the collector, which can cause damage to the collector and break down the fluid. One of the possible solutions is to use façade-integrated solar collectors. It helps to reduce summer peak generation in comparison to roof systems, but it will still be sufficient to heat domestic water and will reduce the potential of overheating (Charron and Athienitis, 2006).

Table 14. Classification of solar combisystems

| Heat storage features | Auxiliary heat management features | Optional features |
|---|---|---|
| **A**: No controlled storage device for space heating | **M:** Mixed mode: The space-heating loop is fed from a combined store charged by both solar collectors and the auxiliary heater | **d**: a drainback system, i.e., a solar thermal system in which, as part of the normal working cycle, the heat transfer fluid is drained from the solar collectors into a storage device when the pump is turned off, and refills the collector when the pump is turned on again |
| **B**: Heat management and stratification enhancement by means of multiple tanks ('distributed storage') and/or multiple inlet/outlet pipes and/or 3-or 4-way valves to control | **P:** Parallel mode: The space-heating loop is fed *alternatively* by the auxiliary heater and by the solar collectors (or a storage unit for solar heat); or there is no hydraulic connection between the solar-heat distribution and the auxiliary-heat emission | **i:** there is a gas or oil burner **i**ntegrated into and sold with the storage device. The **i-**indicator always implies the mixed mode as the auxiliary heat management category |
| **C**: Heat management using natural convection in storage tanks and/or between them to maintain stratification to a certain extent -but without built-in stratification device | **S:** Serial mode: The space-heating loop may be fed by the auxiliary heater, or by both the solar collectors (or a storage unit for solar heat) and the auxiliary heater connected in series on the return line of the space-heating loop | **l**: the combisystem may be used with an auxiliary energy source like wood in the form of **l**ogs, which require a **l**ong running time of the auxiliary boiler at more or less fixed power. A long-running-time auxiliary requires the capability of storing the heat produced until the heat consumers need it. |
| **D**: Heat management using natural convection in storage tanks and built-in stratification devices ('stratifiers') for further stratification enhancement | | |
| **B/D**: Combination of B and D: Heat management by means of natural convection in storage tanks and built-in stratification devices as well as multiple tanks and/or multiple inlet/outlet pipes and/or 3- or 4-way valves to control the flows through inlet/outlet pipes | | |

**Source**: adapted from IEA (2002b)



## III.2 Solar electric technologies

The conversion of the light into electricity is possible due to a physical phenomenon called photovoltaic effect (IEA 1995). The term “photo” means light and “voltaic,” electricity (Tyagi et.al. 2012). The realization of this principle is enabled by photovoltaic technologies (PVs). The main element in the PV is the solar cell, which absorbs sunlight and converts it directly into electricity. It is made of semiconductor material enabling the creation of electrical field (S.

Kalogirou 2009). The light passes through the first thin layer of the cell to the absorber, where the major part of the light is absorbed and free electrons are created due to built-in electrical field. The produced current can then flow through a wire connected to both sides of the cell (IEA 1995). The ratio between the maximum electrical power output and incident light power presents the efficiency of the cell (S. Kalogirou 2009). Different types of the cells have different efficiencies.

Based on the material used solar cells can be categorized into three main groups (Tyagi et.al. 2012):

- Silicon solar cells (see Section III.2.1);
- III-V group solar cells (see Section III.2.2);
- Thin films solar cells (see Section III.2.3).

Depending on whether the PV system is connected to the electricity grid or not, there are:

- Grid-connected systems (see Section III.2.4);
- Stand-alone systems (see Section III.2.5).

If the system uses more than one type of an electricity generator it is usually considered as a hybrid system (see Section III.2.6).

### III.2.1 Silicon solar cells

The cells of this type use silicon as a semiconductor material. Silicon is an abundant and safe raw material that has the potential for high efficiency performance. There are mono-crystalline (single) and poly-crystalline silicon solar cells. Both of them are available on the market and widely used.

Single crystalline silicon cells are one of the most cost-effective solutions because of its low raw material requirements and low production energy requirements. Today the best single crystal Si solar cells have reached an efficiency of 24.7% (Zhao 2004). Commercial silicon solar cell modules can achieve conversion efficiencies around 18% (Tyagi et.al. 2012). Eicker (2001) and Kalogirou (2009) give the range for this parameter 14-15%; Voss et.al. (2001) – 14-18%.

Polycrystalline silicon cells consist of small grains of singlecrystal silicon. They are usually easier to manufacture and, thus, have a lower price (IEA 1995), however, also lower efficiency (Tyagi et.al. 2012). Their efficiency is around 12-13%, according to Kalogirou (2009) and Eicker (2001); 11-15%, according to Voss et.al. (2001).

The third type of silicon solar cells uses amorphous silicon as a semiconductor material. Amorphous silicon is a non-crystalline form of silicon, i.e. its silicon atoms are disordered in structure. Advantages of this type of cells include: high sunlight absorptivity, ability to be deposited on various low-cost substrates (e.g. steel, glass, plastic, etc.) and lower energy input during the manufacturing process (Tyagi et.al. 2012).

### III.2.2 III-V group solar cells

This group of the solar cells includes Gallium arsenide (GaAs) and Indium phosphide (InP) cells. GaAs compound semiconductor is made of two elements - gallium (Ga) and arsenic (As), - which has a crystal structure similar to that of silicon. This material has high level of light absorptivity. Efficiency higher than 18% have been reported in the literature (Yamaguchi and Amano 1985). The GaAs cells are the most popular in space applications.

Another material used for this group of solar cells is Indium phosphide (InP). An efficiency of 22% for an InP crystalline solar cell has been reported in literature. The main disadvantage of using III-V compounds in photovoltaic technologies is the very high cost of production (Tyagi et.al. 2012).

### III.2.3 Thin-film solar cells

This type of PV cells is characterized by a thin layer of semiconductor materials, which is deposited on the supporting layer such as glass, metal or plastic foil. Thin-film materials have higher light absorptivity than crystalline materials.

One of the possible semiconductor materials for thin-film cells is amorphous silicon. The major advantage of amorphous as compared to crystalline silicon cells is the lower need for production energy and, therefore, shorter energy payback time. However, this type of cells has a relatively low efficiency – 5-8% as reported by Eicker (2001) and 4-8% by Voss et.al. (2001). Recent development of thin-film cells is the usage of a cadmium telluride (CdTe) or copper-indium-diselenide (CIS) basis, which should save the material, reduce the costs and increase efficiency (Eicker 2001).

The most advanced type of cell – nano-PV – is under development. Nano-PV relies on coating and flexible polymer substrates with electrically conductive nano-materials (S. Kalogirou 2009).

Solar cells are connected with each other in order to form modules, which are "encapsulated" with different materials to protect the cell and electrical connectors. "A module is a collection of PV cells that provides a usable operating voltage and offers means that protect the cell". Several modules are usually connected in arrays (S. Kalogirou 2009).

Besides the PV arrays, there are certain devices, enabling the use of solar electricity in the building. They include: wires, connectors, inverters, charge controllers, batteries, etc. These devices together with the PV array form a PV system.

All the types of the PV systems presume that the PV array is mounted on the building. They can be placed either on the roof or facades. On the roof they can be either integrated in the roof design (especially for the sloped roof) or placed on the supported structures (e.g. hooks, mounting tiles, racks, etc.). If PVs are installed on facades, they are usually integrated into the walls or placed in the front of the facades to provide shading for glazing elements if needed (IEA 1995). Building Integrated Photovoltaics (BIPVs) provide the optimal and innovative solution from both esthetical and financial (e.g. some money can be saved on roofing and insulation materials if PVs replace part of the roof or wall) point of view (Baechler et al. 2007).

PV systems can be connected to the electricity grid or be stand-alone. For the first type the public electricity grid plays an important role of energy storage. For the second type this function has to be performed by batteries. The third type is hybrid system, which includes the incorporation of the engine generator into the PV system.

### III.2.4 Grid-connected system

For this type of the system a special inverter is required to transform a PV-generated direct current (DC)[17] electricity to the alternative current (AC)[18] electricity in the grid[19] at the level of the grid voltage (S. Kalogirou 2009). Inverters may be installed inside or outside the building, but indoor installations are more common and provide better protection (Baechler et al. 2007).

Connection to the grid gives a great advantage: the excess of electricity generated by the PV during the period with intensive sunshine can be supplied to the grid and vice versa: if the PV production is not sufficient for the building's energy consumption electricity can be taken from



[17] Direct Current is the type of current produced by generators such as batteries or PV modules. It flows in one direction and produces little variation in voltage (Baechler et al. 2007)

[18] Alternating Current is current that alternates between negative voltage and positive voltage with a regular cycle. Most of electric utilities work with AC. Most large household appliances run on alternating current (Baechler et al. 2007)

[19] The grid is a common name for the electric utility companies' transmission and distribution systems (wires and substations) that link power plants to customers through high power transmission line service (Baechler et al. 2007)

the grid. However, in this case the costs of PV electricity must compete against the cost of the conventional energy source used to supply the grid (IEA 1995).

### III.2.5 Stand-alone systems

This type of the system enables a building to be independent from energy infrastructure, which may be beneficial in the remote areas without the access to the public grid (Fieber 2005). In such a system the excess of generated electricity is supplied to the batteries. During the periods of insufficient PV generation the electricity can be taken from the batteries through discharging them. This process is usually supervised by charge controllers to protect the battery from overcharging and increase its lifetime (S. Kalogirou 2009). Like in the grid-connected system the inverter is usually needed in order to transform the electricity to the alternative current required by most appliances (S. Kalogirou 2009). Such systems might be very costly (Baechler et al. 2007) and often require large (even over-sized) PVs and batteries in order to provide the energy independence to the building under different conditions (IEA 1995).

(Fieber 2005) also outlines the opportunity in the future to use hydrogen as storage for PV electricity through water electrolysis. Hydrogen can be stored without losses and converted back to electricity when needed. It makes the vulnerability of PV output less important for the energy demand.

### III.2.6 Hybrid PV systems

Hybrid systems presume the utilization of more than one type of electricity generator (S. Kalogirou 2009). Usually, it is a conventional diesel engine generator as a provider of a back-up power when additional electricity is needed to meet energy demand in the building. One of the best options for the NZEBs is the opportunity to use other RES as a back-up system for the PV.

For example, in areas with high wind speed a wind turbine can be incorporated into the engine generator (IEA 1995). If the wind energy is not applicable, the engine can also be supplied with biofuels (S. Kalogirou 2009).

## III.3 Hybrid solar PV/Thermal technologies

Solar energy is the most applicable and widely used in NZEBs renewable energy source is solar energy, provided by solar collectors and photovoltaic systems. One of the greatest drawbacks of these solar technologies for NZEBs is that they supply different types of energy PVs – electricity and solar collectors – heat, which are utilized for different end-uses: the former – for appliances and lighting, the latter - for hot water and sometimes for space heating. Achieving net zero energy goal may require installation of both types of solar technologies. However, it may cause "battle on the roof" (not enough space on the roof for both PV and solar collectors next to each other) and is usually not the most sustainable and appropriate solution from cost, esthetical and embodied energy point of view (Affolter et al. 2005). One of the possible solutions to this problem is utilization of a photovoltaic/thermal hybrid solar system.

A photovoltaic/thermal hybrid solar collector (or PV/T collector) is a combination of photovoltaic (PV) panels and solar thermal components. A PV/T system is a device that uses PV cells as a thermal absorber to convert electromagnetic radiation into electricity; solar thermal collector converts solar energy into heat and removes waste heat from the PV module. The aim of these components is to use the heat generated in the PV panel in order to generate not only electrical, but also thermal energy (Dupeyrat et al. 2011).

**PV/T system** is a solar technology, which combines a photovoltaic panel and solar thermal components and is able to produce both solar electricity and heat

Conventional PV modules show temperature increase during their operation due to the absorption of solar radiation, as most of it is converted into heat and not into electricity. Therefore, PV cooling is considered necessary to avoid a significant drop in electrical efficiency due to ambient temperature increase. Traditional methods for PV cooling (e.g. air circulation) are usually not effective when ambient temperature exceeds 20°C, which is common for many months in low latitude locations. Hybrid PV/T solar systems combine a simultaneous conversion of solar radiation into electricity and heat. PV/T system usually consists of PV modules and heat extraction units mounted together (Tripanagnostopoulos et al. 2002). Water or air heat extraction allows for decreasing the operating temperature of the PV module, thereby, maintaining its efficiency (Cartmell et al. 2004; Dupeyrat et al. 2011).

There is a number of advantages, which can be offered by a PV/T system:

- the same system can be used to produce electricity and heat output;
- the combined efficiency of the system is usually higher than in case of two independent systems
- the system offers an attractive solution in case the available roof space is limited
- it provides a wide application of energy output
- the system can be easily and cost-effectively integrated into the building, even replacing the roofing material (Hasan and Sumathy 2010)
- the uniform PV/T roof area is more pleasant in terms of aesthetics, than a roof partially covered with thermal collectors and partially with PV laminates (van Helden et.al. 2004).

Despite the outlined advantages, manufacturing of hybrid PV/T systems also involves certain technological challenges. For example, different requirements for the temperature inside the system (lower temperature is more favorable for PV; higher – for the collectors); the necessity for the integrated solar receiver that effectively removes heat from the absorbing (PV) surface in order maintain its performance over the lifetime and under different conditions (Charron and Athienitis, 2006).

Figure 5 schematically presents main advantages and disadvantages of PV/T systems using the approach of the SWOT-analysis.

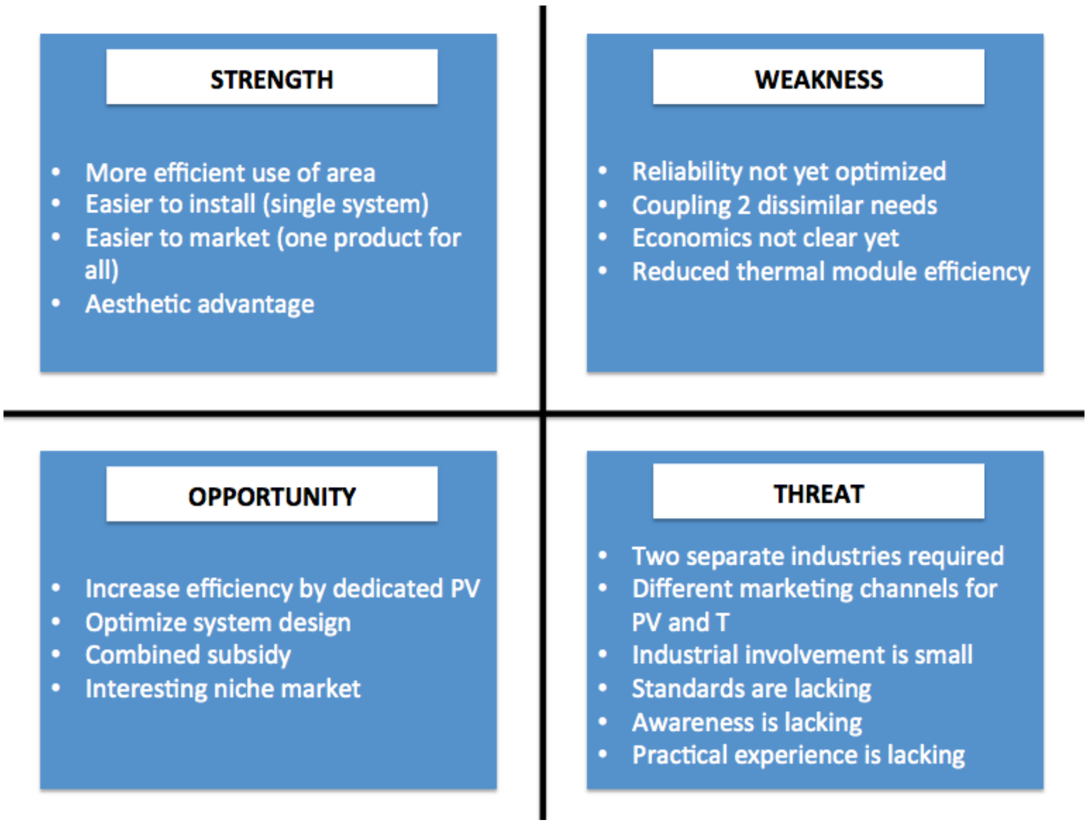



Figure 5. SWOT-summary of advantages and disadvantages of PV/T hybrid solar systems

Source: Zondag et al. (2005)

Different types of PV/thermal collector are present on the market: liquid PV/T collector, air PV/T collector and PVT/concentrator. The following subsections briefly discuss the main types of PV/T systems.

### III.3.1 Liquid PV/T system

This type of PV/T systems is mainly used for water heating and simultaneous production of electricity. The key part of this system is usually similar to a flat-plate collector. A schematic diagram of a PV/T water collector is shown in Figure 6.

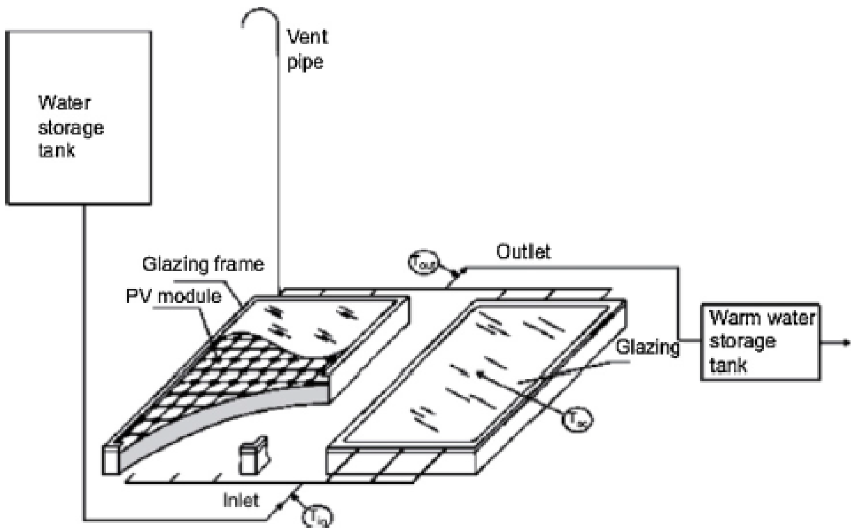



Figure 6. Schematic presentation of a typical PV/T water collector

Source: Tyagi et.al. (2012)

There are uncovered (unglazed) and covered (glazed) collectors and PV/T panels. In case of the former, the absorber is in direct contact with the surroundings, which may cause a substantial heat loss and lower efficiency. Such technologies are more appropriate to serve low-temperature heating applications. In covered PV/T collectors, a transparent cover placed above the absorber transmits about 90% of the incident solar radiation, depending on the material used, providing at the same time a considerable thermal insulating effect and, therefore, increasing thermal efficiency of the system (van Helden et.al. 2004).

On of the key challenges fro the PV/T system design is the trade-off between thermal and electric output. For example unglazed PV/T solar energy systems provide satisfactory electrical output, but the thermal efficiency is reduced especially for higher operating temperatures due to the increased thermal losses from the surface of the PV module. Glazed systems have higher thermal efficiency for a wider range of operating temperatures, but the additional optical losses reduce the electrical output from the system (Souliotis et al. 2008).

Building-integrated PV/T systems are able to generate higher energy output per unit collector area than the conventional solar systems and considered to be more promising than the separated side-by-side installations (Chow et al. 2009). For example, according to simulation results presented in Chow et al. (2009), the photovoltaic/water-heating system is having more economical advantages over the conventional photovoltaic installation in Hong Kong.

Kalogirou and Tripanagnostopoulos (2006) present the simulation results of hybrid prototype models made from polycrystalline silicon and amorphous silicon PV module types combined with water heat extraction units, which show the increase in the overall energy production (although the electric production of the hybrid system is lower than of a conventional PV system).

van Helden et.al. (2004) state that the system calculations indicate higher performance of a PV/T in comparison to the same summed area of PV and thermal collector:

> "for a domestic hot water system with 1m2 of solar thermal collector and 1m2 of PV would together yield 520kWh thermal and 72kWh electrical energy annually, whereas 2m2 of PV thermal collector would yield 700kWh thermal and 132kWh electrical" (van Helden et.al. 2004).

The authors point out that higher yield from the PV/T system is especially beneficial if there is a "competition on the roof" and demonstrate that with a PV/T system also a shorter payback period can be achieved in comparison to conventional PV panels (van Helden et.al. 2004).

Dubey and Tiwari (2009) have observed that water heating collectors partially covered by PV module are beneficial in terms of annualized uniform costs for the users whose main demand is in hot water production, while collectors fully covered by PV are more applicable for the users with higher demand for electricity generation.

Figure 7 shows typical thermal efficiency curves for covered and uncovered PV/T. The collector's efficiency is plotted versus the difference between fluid inlet temperature and ambient temperature, divided by the incident solar radiation.

The slope of the thermal efficiency curve is a direct measure of the thermal loss coefficient. Figure 7 clearly shows that an uncovered collector has lower thermal efficiency than a covered one, mainly due to higher thermal losses (van Helden et.al. 2004).

Electric efficiency, on the contrary, is lower in case of glazed systems due to additional optical losses (see Figure 8).

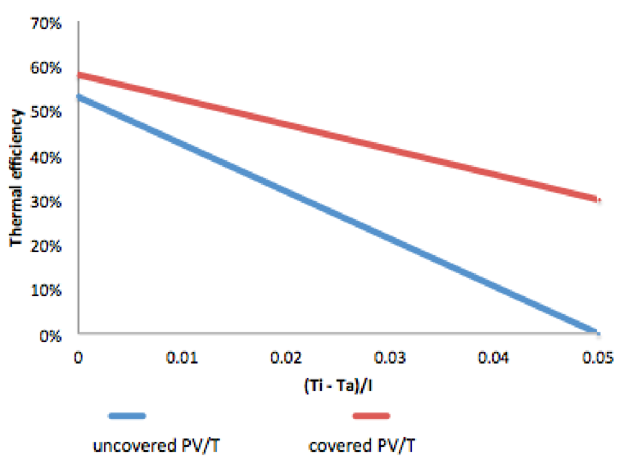



Figure 7. Thermal efficiency curves for typical covered and uncovered PV/T collectors

Source: adapted from van Helden (2004)

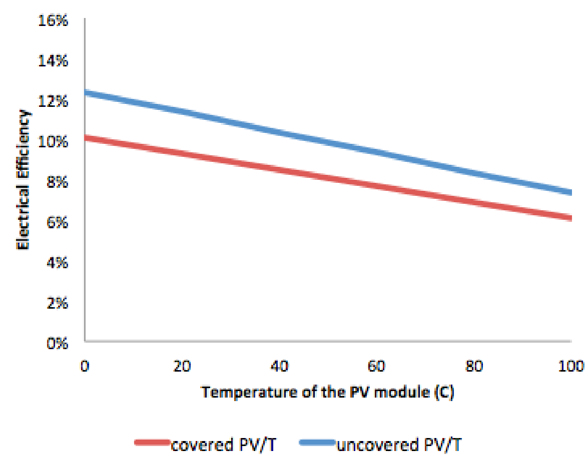



Figure 8. Electrical efficiency curves for typical covered and uncovered PV/T collectors

Source: adapted from Souliotis et al. (2008)

### III.3.2 Air PV/T system

In this type of a PV/T system air is used instead of water in the previous type as a heat transfer fluid. Although air PV/T systems usually demonstrate lower efficiency than that of a water PV/T system due to their relatively poor thermophysical properties, air-based systems may be preferred in many practical applications due to minimal use of materials, low construction and operating costs (Tyagi et.al. 2012; Tonui and Tripanagnostopoulos 2007).

Aste, et.al. (2008) have demonstrated experimental and theoretical results on the design, development and performance monitoring of a hybrid PVT air collector. The authors also developed a simulation model for performance prediction of the system.

Tonui and Tripanagnostopoulos (2007) investigated the performance of two low cost heat extraction improvement modifications in the channel of a PV/T air system to achieve higher thermal output and PV cooling and at the same time to keep the electrical efficiency at acceptable level.

Sarhaddi et al. (2010) have developed a detailed model to calculate a number of thermal and electrical parameters of a typical PV/T air collector. The authors have found the thermal efficiency, electrical efficiency and overall energy efficiency of the PV/T air collector is about 17.18%, 10.01% and 45%, respectively, for a sample climatic, operating and design parameters.

### III.3.3 PV/T concentrator

Concentrating photovoltaic (CPV) systems can operate at higher temperatures than those of the flat plate collectors. The use of CPV/T in combination with concentrating reflectors can potentially increase the power production from the system significantly (Tyagi et.al. 2012).

Hj. Othman et al. (2005) present the results for performance investigation of a double-pass photovoltaic thermal solar air collector with compound parabolic concentrator (CPC).

The results of the study show the decrease in electricity production of the PV/T system when the increase in the airflow temperature takes place. The designed hybrid system has a high potential to significantly increase the power production and reduce the cost of photovoltaic electricity.

Kostić et.al. (2010) have designed an optimally oriented and movable PV/T collector with flat reflectors mounted on it in order to increase thermal and electrical energy generation. The daily test results of PV/T collector without and with reflectors in optimal position in the period June–September 2008 have shown that the thermal and electrical efficiencies of PV/T collector with reflectors are slightly lower than of the one without reflectors due to the solar radiation intensity concentration factor. However, the total thermal and electrical energy generated by PV/T collector with reflectors are significantly higher than total thermal and electrical energies generated by PV/T collector without reflectors. Both PV/T systems show higher efficiencies and energy generation than a conventional thermal solar thermal collector (Kostić et.al. 2010).

Coventry (2005) reports the overall measured efficiency of 69% (thermal efficiency - 58% and electrical efficiency - 11%) of a designed parabolic trough photovoltaic/thermal collector working under typical operating conditions show

### III.3.4 PV/T successful case studies

A real life example of a successful PV/T system can be the public library at Mataro, near Barcelona. The opaque and semi-transparent hybrid PV/T modules installed at the main façade of this building supply electricity and heating to the building, while maintaining daylight penetration with reduced risk of summertime overheating. Each hybrid element is supplied by a ventilated chamber, which enables warm air to be generated via natural convection from PV surfaces. This pre-heated air is feed into a conventional gas heating system, where it is brought up to supply temperature. During warm seasons, surplus heated air within the façade is vented to the exterior, thereby maintaining PV cell efficiencies (Cartmell et al. 2004).

Another example is The Brockshill Environment Centre located in the city of Leicester, UK. This building has a ventilated photovoltaic and solar air system, which produces electricity and heats the air for space heating. The results of the energy consumption and production monitoring show that PV/T contribution exceeds the auxiliary heat in most of the months (Cartmell et al. 2004).

PV/T is a relatively new technology, however, it is considered as a promising state-of-the-art solution for building on-site renewable energy generation and is expected to spread on the market as demand grows (Coutts 2011 - pers.com.), however, no substantial steps have been taken towards reducing their cost and making them more competitive (Tyagi et.al. 2012).

Installation of PV/T systems provides the opportunity to significantly increase generation of solar energy for different end-uses in comparison to separate systems occupying the same roof area.

# IV CHAPTER. THEORETICAL FRAMEWORK

In order to answer research questions and achieve the main research aim a combination of energy modelling with GIS (Geographic Information System) analysis was used in this PhD research.

GIS analysis gave the opportunity to prepare and analyse the data on climatic conditions, rooftop areas and availability of solar energy in different locations worldwide.

Energy modelling helped to answer most of research questions by estimating, on the one hand, building energy demand for different end-uses, and, on the other hand, solar energy production. Basing this analysis on GIS data gave the opportunity to indicate the locations, where NZEBs, according to the chosen definition, are not technically feasible. The further analysis of the energy modelling results allowed for calculating potential for covering building energy use by building-integrated solar energy technologies.

Both methods are discussed in more details below (see Section IV.1 and IV.2, respectively).

## IV.1 Energy modeling

According to the literature there are two main approaches to energy modeling: bottom-up (synthesis) and top-down (decomposition) (IPCC 1996, Novikova 2010, Novikova 2008, Böhringer and Rutherford 2007, Richards 2011, Repetto and Austin 1997, Böhringer and Rutherford 2006, Rivers and Jaccard 2005, Cunha da Costa and Fallot 200), Wing 2006).

This division occurred after first oil crisis, which caused considerable changes in the approaches to energy systems' analysis. Before the shock energy models were focusing on supply-side, considering energy demand as exogenous variable, as income-elasticity remained rather constant. However, after the first oil shock certain changes took place in energy sector, having caused significant variations in income elasticity. First of all, the tertiary sector gained the leading role in the developed countries, having shifted the energy consuming industries to the developing world. Secondly, many countries started setting up local energy production in order to substitute imported oil, which had become much more expensive. Thirdly, increased energy prices and limitations for energy production stimulated technical progress and increased the number of technical innovations (Cunha da Costa and Fallot 2002). The necessity for new approaches to energy systems' analysis, which could consider these changes, became obvious. It leaded to the upraise of the top-down versus bottom-up debate.

Generally, in energy analysis the top-down models study the relations between energy and macro-economic variables, while bottom-up modeling analyzes individual technologies, incorporating them into a larger energy system (Novikova 2010, Novikova 2008).

### IV.1.1 Top-down modeling

IPCC (1996) gives the following definition of top-down models:

> "Top-down models are aggregate models of the entire macroeconomy that draw on analysis of historical trends and relationships to predict the large-scale interactions *between* the sectors of the economy, especially the interactions between the energy sector and the rest of the economy".

Therefore, top-down models use aggregated macroeconomic data (economic indices, prices, elasticities (Richards 2011) and production functions for each sector of economy (McFarland, Reilly, and Herzog 2004). The main focus of these models is the whole economy and market interactions and feedback of these interactions to energy policies (Jaccard and Bailie 1996, (Böhringer and Rutherford 2006).

Cunha da Costa and Fallot (2002) distinguish between two main types of top-down models: neo-Keynesian and Computable general equilibrium models (CGEMs). The models of the first type are macroeconomic techniques, which usually gain the results through utilization of production functions with capital (K) and labor (L) as the main input variables. Additional production factors, which may be included in the function, are energy (E) and materials (M) (KLEM function). If more than these four production factors are considered the input-output tables are used in order to describe the relations between sectors.

Production functions present the relationships between variables, which resulted from statistical estimation in the past and have developed since then (Repetto and Austin 1997).

The second type refers to the "Walrasian intertemporel equilibrium models that stressed the supply effects". CGEMs are based on the assumption that relationships between demand and supply are based on rational resource allocation, utility maximization, cost minimization and market equilibrium for all goods, the prices of which equal the marginal production costs. CGEMs give the opportunity to analyze the feedback between energy system and other sectors of economy and make the comparisons between energy market and the whole economy and among different economies at the international level (Cunha da Costa and Fallot 2002). A drawback of this type is that the supply and demand conditions are usually based on statistically estimated trends in the past (Repetto and Austin 1997).

Novikova (2008) proposes similar types of top-down models, presenting input-output models as a separate type:

- *Input-output models* "describe the complex interrelationships among economic sectors using sets of simultaneous linear equations with fixed coefficients". The models of this type consider aggregated demand exogenously and provide the details for each sector on how it can be met.
- *Keynesian or effective demand macroeconomic models* describe investment and consumption patterns in different sectors of economy. They often include forecasts built with macroeconomic and econometric techniques on the basis of data series. Such models allow for measuring the influence of policies' introduction on macroeconomic indicators (economic growth, employment, etc.)
- *Computable general equilibrium models* (CGE) evaluate the behavior of economic actors on the basis of microeconomic principles. The main aim of such models is to simulate the behavior of key market parameters, e.g. production or exchange rate, by

> using the equations of economic actors' behavior and analyzing them in different states of equilibrium.

The obvious drawback of top-down modeling is that dealing with highly aggregated data on macro level, they are unable to consider the processes on the lower levels of analysis (e.g. adoption of a discrete technology) (Böhringer and Rutherford 2006). Top-down analysis is unable to capture the whole process of the technological change and has the tendency to overestimate the costs of energy or mitigation policy implementation (Wing 2006).

### IV.1.2 Bottom-up modeling

Bottom-up approach is closely related to energy engineering and accounts for "physical flows of energy capital equipment" (Worrell, Ramesohl, and Boyd 2004). The models of this approach focus on the energy demand-side and allow for calculating total energy consumption in a country by summing up the energy consumption of different economic sectors (Cunha da Costa and Fallot 2002).

Bottom-up models are more appropriate for technological assessment (Novikova 2010), as they include thorough data on technologies and costs, which allow for describing energy consumption in great detail (IPCC 1996). The technologies' data among others typically include engineering information on life cycle costs and thermodynamic efficiencies (McFarland, Reilly, and Herzog 2004).

According to Worrell, Ramesohl, and Boyd (2004), bottom-up models differ on the basis of content and scope ("the degree of activity representation, technology representation, and technology choice"), the aim and degree of macroeconomic data integration.

Depending on their goal and scope, Worrell et al. present three types of models:

> *Optimization models* are used to find the optimal set of technology choices to achieve a specified target at the lowest costs.

*Simulation models* provide a quantitative illustration of exogenously defined scenario strategies.

*Integrated models* include the interaction between changes in energy use and the economy instead of using a preset economic development scenario (Worrell, Ramesohl, and Boyd 2004).

Novikova (2010) outlines a similar classification of bottom-up models related to the evaluation of technological potential:

*Scenario models,* which construct a storyline with the implementation of certain technological changes (usually improvement), and a reference baseline without significant changes; the potential is calculated as a difference between the reference baseline and the scenario with technological changes.

*Potential estimates*, which often take a form of *energy efficiency supply curves* characterizing the potential as a step-wise function of marginal costs per unit of energy saved, with each step representing a certain energy efficiency measure.

*Optimisation models,* which aim to find the optimal allocation of resources and other factors, for instance, investments required or the technology penetration rate needed to allow sectoral energy consumption for meeting a target at minimal costs.

Cunha da Costa and Fallot (2002) added two more types of the bottom-up models - accounting and techno-econometric - to simulation and optimization types. Accounting models represent “the first generation of bottom-up models”. They do not include dynamic changes and most of variables are exogenous. Techno-econometrical models are able to identify structural and behavioral changes as they present energy savings within economic interactions. However, their results may be biased by untypical data. Simulation models are considered to be more advanced than two first types as they rely on observed data with some assumptions on technologies' adoption and are able to take into account market imperfections. Optimization models differ from the simulation ones through taking into account consumer choices. They assume a rational consumer, who has full information about market circumstances and always chooses the best options. Therefore, it is difficult to include market imperfections in this type of models (Cunha da Costa and Fallot 2002).

Worrell et al. propose three main factors, which influence technology choice during bottom-up modeling regardless of the model's type:

> 1. The state and availability of the current and emerging technology;
>
> 2. Economic costs, i.e., energy prices and equipment costs feed into technology choices as the model looks at life-cycle costs for various equipment choices;
>
> 3. Operational decision rules, which are expressed as a rate at which ideal energy intensity is approached, embedded in discount rates, or is reflected in the way cost calculations are done (Worrell, Ramesohl, and Boyd 2004).

Besides technological analysis bottom-up models often include economic estimations, such as energy expenses and investment costs. The detailed information on available technologies and their efficiencies gives the opportunity to model the direct cost and benefits of incremental investments in energy efficiency and switching to "cleaner" fuels (Jaccard and Bailie 1996). The results from individual sectors may be then aggregated in order to estimate the overall technological and/or economical potential for energy and/or emissions reduction (Repetto and Austin 1997).

However, compared to top-down models, they are typically unable to track the interactions between energy sector and other sectors of the economy (IPCC 1996). Bottom-up models also have a weakness in measuring the effects of the changes occurring on the microeconomic level on the situation on the macro-economic level (Cunha da Costa and Fallot 2002). Another drawback of these types of the models is that they may overestimate the potential penetration of a technology as they take energy prices and some other variables exogenously (McFarland, Reilly, and Herzog 2004). A high number of exogenous variables might cause significant deviations from reality (Cunha da Costa and Fallot 2002). Bottom-up models are often characterized by "technological optimism", which means lower than in reality costs of, for example, mitigation or technology's adoption (Wing 2006).

The features of the bottom-up and top-down converging adopting characteristics one another (Richards 2011). A bottom-up model can be integrated into a bigger economic model. The link to the economy allows for cost-benefit analysis of different scenarios (Worrell, Ramesohl, and Boyd 2004). It gives the ground for occurring of the methodologies combining two approaches, so-called hybrid models.

### IV.1.3 Hybrid models

Hybrid models combine certain features of both bottom-up and top-down approaches and, ideally, aim at overcoming weaknesses of the traditional approaches and integrating their strengths. Such a model would include detailed information on specific technologies (as bottom-up approach) together with real market data in order to explain behavior of economic actors and interactions between economic sectors (as in top-down approach). However, it should be noted that in reality it is rather difficult to realistically present economic actors' behavior at the technology-specific level (Wing 2006).

Two possible types of hybrid models may be outlined: one moving from top-down approach to bottom-up and the other one moving in the opposite direction (Novikova 2008).

(Böhringer and Rutherford 2006) use different approach to classifying hybrid models. The first group includes the models resulted from coupling existing top-down and bottom-up models (e.g. Hudson and Jorgenson 1974). Böhringer and Rutherford state that such models may face the problems with consistency of the results due to their complexity. The second group of the hybrid models presumes constructing an integrated modeling framework, which combines top-down and bottom-up features.

For the model developed during this research an integrated framework combining bottom-up approach with certain top-down data has been developed (see Chapter V for more details).

Regardless, what modeling approach is being used in research, one of the key necessary procedures is data gathering. Data can come from different sources: government statistics, publications, experiments, measurements, etc. A very important question in this regard is reliability of the data. Not all the sources of information offer the data, which can be trusted. Therefore, it is the task of the researcher to verify that gathered data are trustworthy and will not distort the results. One of the ways to gather the data and conduct the preliminary analysis before doing energy modeling in this research is GIS (Geographic Information System) analysis. It is discussed in more details below.

## IV.2 GIS analysis

Geographic information systems were developed as "tools for the storage, retrieval and display of geographic information" (Fortheringham and Rogerson 1994). GIS gives the opportunity to "study and understand the real world processes by developing and applying manipulation, analysis criteria and models and to carryout integrated modeling" (Raju 2011).

Câmara et al. (2008) outline the following components of GIS:

- User interface;
- Data input and integration;
- Graph and image processing functions;
- Visualization and plotting;
- Data storage and retrieval.

GIS is a reliable technique for data collection, storage and analysis. In 1994 Fortheringham & Rogerson had already reported that GIS is receiving the increased interest from researchers working in various fields and the number of GIS users is "beginning to mature". The investigation of GIS methods resulted in publishing practical case studies performing different ways and combination of techniques in solving concrete applied problems (Fortheringham and

Rogerson 1994). Miller (1999) also pointed out the increased interest in GIS and its multidisciplinary character.

### IV.2.1 GIS and spatial analysis

GIS has now become an even more powerful tool, especially in the light of developing comprehensive and user-friendly software (e.g. ArcGIS), which can be used in any field, where spatial data and analysis are needed. Spatial analysis is one of the techniques used in GIS, which may be defined as "a general ability to manipulate spatial data into different forms and extract additional meaning as a result" (Fortheringham and Rogerson 1994). The main aim of spatial analysis is "to measure properties and relationships, taking into account the spatial localization of the phenomenon under study in a direct way" (Câmara et al. 2008).

According to Câmara et al. (2008), the greatest benefit of spatial analysis is the ability to visualize spatial patterns of various phenomena (e.g. population, weather, climate characteristics, economic indicators and many others) in the form of colorful maps. Moreover, spatial analysis is able to transfer the presented patterns into "objective and measurable considerations" (meaning numerical data in the form of tables and/or charts) (Câmara et al. 2008).

In order to perform spatial analysis certain input geographic data are needed. These data may be presented in different forms. Table 15 outlines three main types of spatial data.

Table 15 notes three types of geomentric data representation used in GIS spatial analysis: points, samples and polygons. There are two more types, which should be noted: grid and image. The definitions of each type given below are adopted from Câmara et al. (2008)

> A *point* is an ordered pair *(x,y)* of spatial coordinates, which indicates the place of occurrence of an event.
>
> *A sample* is a set of ordered pairs *{(x,y,z)}* where the *(x,y)* pairs indicate the geographic coordinates and *z* indicates the value of the studied phenomenon for that localization.

A *polygon* is a set of ordered pairs {(x,y)} of spatial coordinates, in such a way that the last point is identical to the first; each polygon can delimit an individual object.

*A grid* is a matrix associated with a region on the earth surface, where a numeric value is assigned to each element.

An *image* is a matrix for the graphic presentation of a grid, where each element is associated with an integer value (usually in the 0 to 255 range).

As can be seen, different types of the data contain different information and can be used for different analytical purposes. Five data types outlined above can be grouped into two broader categories: vector (includes point, sample and polygon) and raster (includes grid and image) data[20]. Usually, modern GIS software packages provide the opportunity to convert data from vector to raster and vice versa. Generally, raster data are more suitable for representing geographical phenomena (ESRI 2001), allowing for storage of a large amount of information and application of a broader range of analytical tools.

Table 15. Types of data in spatial analysis and their applications

| Data type | Analysis type | Description | Aim | Examples of data |
|---|---|---|---|---|
| **Localized events or points** | Events or point patterns analysis | Phenomena expressed through occurrences identified as points localized in space | Studying the spatial distribution of the datapoints and identifying the patterns, regularity or casuality of their allocation | crime spots, disease occurrences, and the localization of vegetal species |
| **Samples of fields and matrixes** | Surface analysis | Data estimated from a set of field samples that can be regularly or irregularly distributed | Reconstructing the surface from which the samples were removed and measured and quantifying spatial dependence among the sample values | soil types, ecosystems, topography |
| **Polygons and attributes** | Areal analysis | Means data referred to individuals situated in specific points in space, aggregated in analysis units, usually delimited by closed polygons | Analyzing socio-economic data and its distribution patterns in a certain area | census tracts, postal addressing zones, municipalities |

**Source**: adapted from Câmara et al. (2008)



[20] In the raster format, the graphic is represented as a combination of individual "units", where each unit can represent only one value. In the vector format, the graphic is represented by a set of points, joined by a certain relationship or function (Wolfe 2000).

### IV.2.2 Spatial analyst of ArcGIS

The most recent, state-of-art software for GIS analysis is ArcGIS developed by Environmental Systems Research Institute, Inc (ESRI)[21]. ArcGIS has a special module for spatial analysis, called Spatial Analyst (SA). SA has the capacity to:

> "…create, query, map and analyze cell-based raster data; perform integrated raster/vector analysis; derive new information from existing data; query information across multiple existing data layers; and fully integrate cell-based raster data with traditional vector data sources" (ESRI 2001).

SA works with different data formats, which makes it a very flexible tool. It includes a number of various analytical tools and allows for powerful visualization of results. According to McCoy and Johnston (2002), SA gives the opportunity to:

- *Derive new information* (e.g. reclassification, surface estimation, population density, slop, aspect, etc. calculation)
- *Identify spatial relationships* (certain features or areas of different raster datasets can be, for example, overlaid or extracted; a function of map algebra allows for algebraic operations between different raster datasets)
- *Find suitable locations* (combining different dataset gives the opportunity to find a suitable location for particular objectives, according to multiple criteria)
- *Calculate travel costs* (the tool, which allows for creating travel surfaces for finding optimum corridors across the surface)
- *Work with cell-based GIS data* (SA gives the opportunity to combine data of any raster types).

There is a great variety of techniques incorporated into SA to perform these and many other tasks. It is not the purpose of this paper to overview all of them, however, the most important of them are briefly presented in Table 16.

Therefore, SA provides a very rich variety of techniques, which can be used for a very comprehensive spatial analysis or for rather simple operations, producing new data for further analysis. One of the possible ways to utilize SA and GIS, in general, is to analyze the renewable

[21] http://www.esri.com/

energy potential of a certain territory. Some analytical efforts made in this field and described in the literature are summarized in Section IV.2.3.

Table 16. Selected techniques of ArcGIS Spatial Analyst Tool

| SA technique | Opportunities of analysis | Possible results of analysis |
|---|---|---|
| **Raster calculator** | To perform queries across different raster datasets; make any algebraic operations between features of different datasets | New more informative data, which may be presented in visual or quantitative form |
| **Density analysis** | To measure the quantity of an input feature data sets distributed throughout a landscape. The density value is calculated for each cell in the final raster | Presentation of features concentration and location |
| **Cell statistics** | To analyze and visualize changes in the data over time; to calculate different statistics for each cell: mean, maximum, etc. | Presentation and visualization of temporal trends, which might be taking place in data |
| **Zonal statistics** | To calculate statistics for each given zone of a zone dataset based on the features from another dataset | Calculation of the statistics for each zone |
| **Surface analysis** | To analyze topographic information of a certain area, such as hillshade, slope, aspect, viewshed, etc. | Visualization of different topographic aspects of the area or usage of the topographic data for more advanced spatial analysis |
| **Spatial modeling** | To solve different geospatial tasks, such as finding optimal location for a certain purpose; calculating distances between objects; modeling water flow; analyzing different characteristics of a phenomenon (e.g. pollution) in different locations | Presentation and visualization of the results for suitability modeling, distance modeling, hydrology modeling, surface modeling, etc. |

**Source**: adopted from (ESRI 2001)

### IV.2.3 Renewable energy potential evaluation with GIS

GIS and SA are very useful tools for solving the tasks regarding renewable energy. All renewable energy sources presume utilization of natural resources (sun, wind, water, geothermal heat, etc.), at the same time renewable energy production depends greatly on local conditions (climate, soil type, land use, topography, etc.). These factors have to be taken into account during the evaluation of renewable energy potential, which requires collecting and analyzing spatial data for certain area(s). As has been shown earlier, such tasks may be successfully solved by means of GIS.

The studies, which use GIS for renewable energy potential evaluation, can be divided according to the energy sources they analyze: usually it is biomass, solar electricity (PV), solar thermal and wind.

Voivontas, Assimacopoulos, and Koukios (2001) estimate the potential for power production from agriculture residues. GIS analysis is used for identification of the geographic distribution of the available, technological and economically exploited biomass potential. To perform this task the authors used GIS spatial aggregating and querying tools.. The developed methodology was applied for the case study of Crete. A number of datasets was included in the analysis, such as data on administrative boundaries, town location and other demographic data, the high-voltage grid network, location of roads, cultivated areas and types of cultivation, the characteristics of the residues produced from the major crops cultivated in Crete. The study shows that there is a great economic potential for energy production from biomass in Crete.

Another study on biomass potential - Fiorese and Guariso (2010) – analyzed the potential of energy production from arboreous and herbaceous dedicated crops in Emilia-Romagna (Northern Italy). GIS was mainly used for finding an optimal location for biomass plant including the analysis on land suitability and land availability. The input data for GIS analysis was also diverse: digitized cartography for soil characteristics, qualitative descriptions of cultivar agronomic needs, and numerical data for land use. The results showed a great potential for growing energy crops in this part of Italy: devoting only 2% of agricultural lands in the region would increase the share of renewable energy in electricity production by 58%.

Carrion et al. (2008) used GIS to evaluate suitable sites for the construction of solar power plants in order to produce electricity in Spain. The input data for GIS analysis include the information on global solar irradiation on horizontal surface, average annual temperatures, slope angles, protected areas and land use. The authors set a list of criteria, which a suitable for a solar power plant site should correspond to (e.g. slope less than 2%, low agricultural value, etc.). After this they have analyzed different datasets together by means of SA and found locations optimal for potential plants. Then, taking into account solar radiation data and average temperature values in these locations, electricity capacity of potential solar power plants have been estimated.

A number of studies, which consider energy production from roof-mounted PVs, use GIS for evaluating roof area suitable for solar systems (usually PV or solar collectors for domestic hot water heating) installation. Such analysis gives the opportunity to evaluate total roof area in the analyzed region and then by means of energy modeling calculate potential solar energy output. The examples of such studies are: Bergamasco and Asinari (2011a) for North-Western Italy, Wiginton, Nguyen, and Pearce (2010a) for South-Eastern Ontario and Izquierdo et al. (2011) for Spain. The methodologies presented in these studies differ, but common features include the analysis of global solar radiation data, roof area available for solar systems and solar systems' performance.

Charabi and Gastli (2011) used a similar approach for estimating potential energy production of large PV farms in Oman. By means of GIS analysis the study assessed land suitability and availability for such installations considering different PV technologies. Janke (2010) also assessed suitable land for solar farms in Colorado. Besides, the author considered the construction of wind farms in the region. Like Charabi and Gastli, Janke used several criteria, which defined areas suitable for the farms. Available locations for wind farms, according to defined criteria, are also investigated for Poland in Sliz-Szkliniarz and Vogt (2011) and for Turkey in Aydin, Kentel, and Duzgun (2010). In studying wind energy potential GIS also assisted for wind farms output calculation as it allows for analyzing the data on wind speed for the chosen location (Sliz-Szkliniarz and Vogt 2011).

### IV.2.4 Power of combining GIS analysis with energy modeling: justification of the chosen theoretical framework

As it was presented in the two previous sections, GIS analysis provides a wide range of opportunities for analyzing the potential for most of renewable energy sources. It gives the opportunity to find an optimal location for a wind farm or solar power plant or assess the availability of renewable energy sources in a certain location by analyzing spatial and geographical data. Most of the studies reviewed in Section IV.2.3 use GIS analysis in the beginning of the analysis and then complete the research task by means of energy modeling. The literature review has demonstrated the applicability and reliability of these methods' combination in scientific research in the energy field.

Such a combined approach, which includes both energy modeling and GIS analysis, has been chosen for this PhD research for several reasons:

1. Analysis of solar energy potential: such an analysis requires consideration of a number of climatic and geographical parameters, as well as their dynamics over the time (e.g. within a season, month, day, etc.). Such data is quite difficult to obtain from sources other than GIS datasets, especially for multiple locations. Moreover, even if the data is acquired, it has to be stored and processed in a certain system or software that would allow for performing certain operations, according to the calculation mechanism. GIS is, probably, one of the easiest and most accessible frameworks, which can allow for doing this.

Therefore, GIS dataset were considered as the main source of reliable input data for solar energy potential calculation in this research.

2. Global geographical coverage: as this PhD research presumes the analysis on both regional and global level, it has to account for the diversity in a number of parameters in numerous locations. The resolution of this data has a direct impact on the robustness of the results. GIS analysis gives the opportunity to operate with the datasets of a high resolution and perform a high quality analysis even on the global scale.
3. Importance of solar energy systems' performance: as it has been pointed out about GIS datasets provided key input data for the analysis, however, the calculation of potential solar energy supply is not possible without taking into account the performance of the solar energy systems and their behavior under changing weather and climatic conditions. Energy modeling gives the opportunity to consider such processes, as well as the systems' characteristics, which influence the final energy output. Therefore, in this research GIS provides the opportunity to obtain, process and pre-analyze the necessary input data, while energy modeling uses the results of the GIS analysis for further calculations, according to the established methodological algorithm.
4. Need for the energy balance calculation: analysis of the technical potential for solar-supplied NZEBs requires calculation of the energy balance, i.e. both solar energy supply and energy demand in buildings. Estimation of the solar energy supply is the main focus of this PhD research and the importance of the combined approach has been discussed above. However, such an analysis of the potential has to be performed and structured in a way to enable the comparison of the estimated solar energy supply to building energy demand. The estimations for the latter are available from the external sources (see

Sections V.1.1 and V.1.2). Therefore, the output of the potential solar energy supply calculations has to have a similar structure to ones these external data sources have. Such adaptation of the output's structure can be done through the energy modeling, using certain methodological features of these external sources.

In the light of the above the combined approach (see details in Chapter V) was considered as the optimal solution for achieving the research goals and obtaining robust results.

# V CHAPTER. RESEARCH DESIGN AND METHODOLOGY

Previous chapter describes various approaches to energy modeling, as well as the power of the approach, which combines energy modeling and GIS analysis. Based on the analysis of potential theoretical frameworks bottom-up modeling with certain elements of top-down approach in combination with GIS analysis was determined to be the most appropriate framework to achieve the outlined research aim.

This chapter describes research design and methodology grounded on this theoretical framework and implemented through computer-based modeling.

Mathematical and computer-based modeling is a useful tool, which provides various stakeholders (e.g. policy-makers, academics, experts, etc.) with the opportunity to better understand present and future processes and assess the long-term and complex impact of policy matters (Boulanger and Bréchet 2005).

## V.1 Research Design

The research design constitutes to the overall strategy chosen to integrate different components of the study in a coherent and logical way, ensuring that the research problem will be effectively addressed. Research design contains the discussion on the collection, measurement, and analysis of data.

Figure 9 illustrates the overall logic of the research design for this dissertation.

Input data for this study are mainly related to climatic and geographical parameters (different types of solar radiation, wind speed, ambient temperature, etc.), which allow for calculating solar energy outputs.

It can be seen that there are three main outputs of the study: (1) estimation of [present and future] energy use in buildings, (2) estimation of [present and future] potential solar energy production in buildings through building-integrated solar energy technologies and (3) the conclusion on technical potential of NZEBs (supplied only by solar energy) for different building types and climate zones, based on respective comparison of potential solar energy supply to estimated building energy demand.

As the main focus and contribution of this dissertation is estimating of the potential solar energy production in buildings and drawing conclusions on feasibility of NZEBs, the results for the building energy use with certain modifications are coming from already existing studies, namely High Efficiency Building (HEB) Model developed by Centre for Climate Change and Sustainable Energy Policy (3CSEP) at Central European University (CEU) (for more details see Sections V.1.1 and VII.2) and Bottom-Up Energy Analysis System (BUENAS) Model (for more details see Sections V.1.2 and VII.3) .

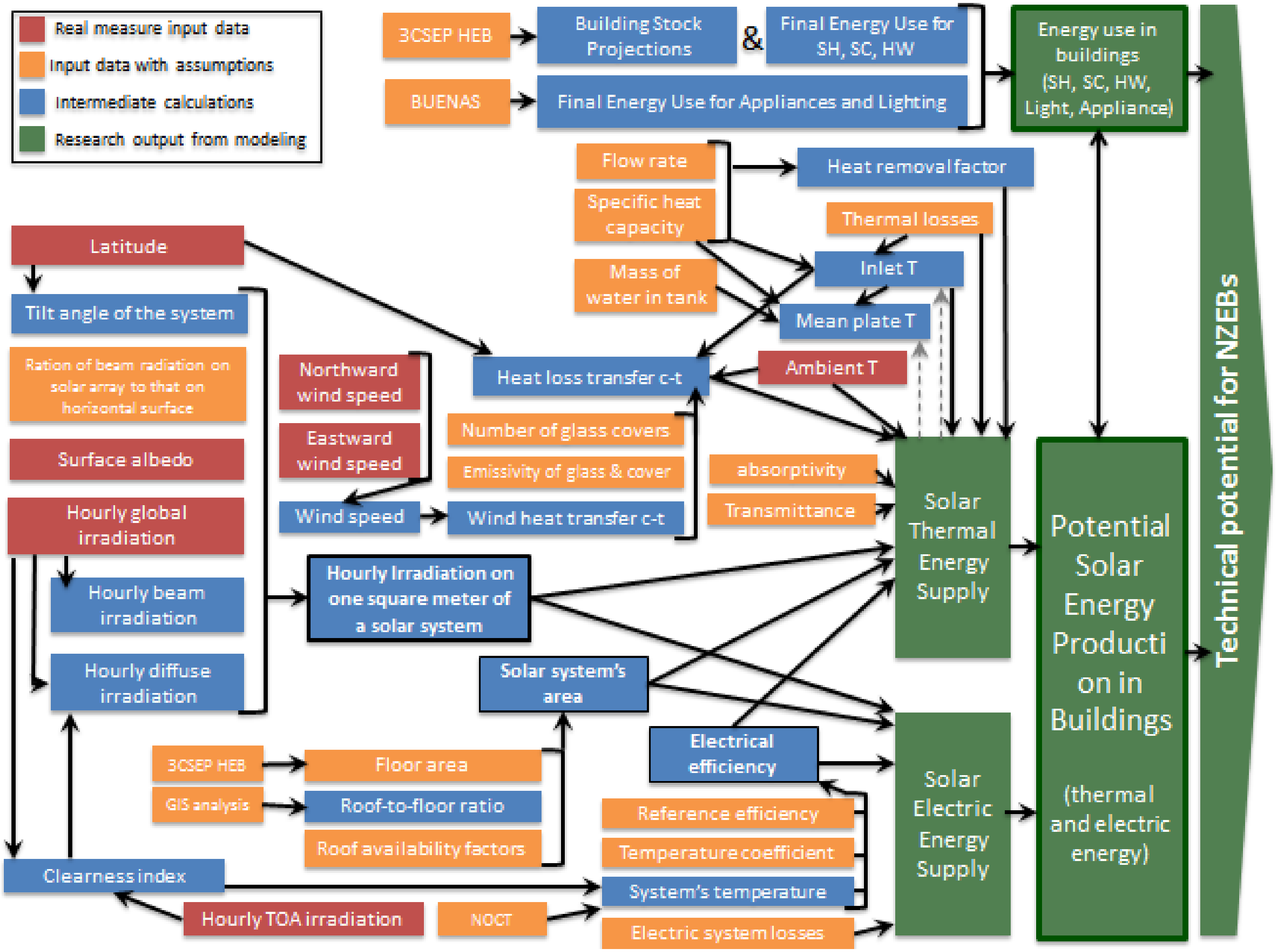



Figure 9. Schematic Presentation of Research Design

### V.1.1 Estimation of building thermal energy demand – 3CSEP-HEB model

3CSEP-HEB Model had been elaborated by 3CSEP under the umbrella of Global Building Performance Network (GBPN) (Urge-Vorsatz, Petrichenko, et al. 2012) based on scenario work accomplished for Global Energy Assessment (GEA) (Urge-Vorsatz, Eyre, et al. 2012). The first results of this long-term effort based on the teamwork of several researchers (including the author of the paper) were gained in March 2012.

The building energy use model is novel in its methodology as compared to earlier global world energy analyses and reflects the new emerging paradigm in building energy transformation. A new paradigm focuses on a performance-oriented concept of building energy use as opposed to a component-oriented approach. In other words, it considers a building as a complex system rather than a sum of separate components.

The model considers three end-uses: space heating, space cooling and water heating. It provides the results at three levels: global (results for the whole world), regional (for 11 regions) and national (for selected countries, namely US, China, India, EU-27 members). Regional division of 3CSEP-HEB Model serves as a base for the model elaborated for this dissertation (see Figure 10). Most of the results in this dissertation is presented for all or some of the 11 large regions and not for the countries in order to ensure a broader geographical coverage and consistency of the scale for the results' presentation. For more details on the regional division, full names of the regions and countries considered in each region – see ANNEX A. REGIONAL DIVISION.

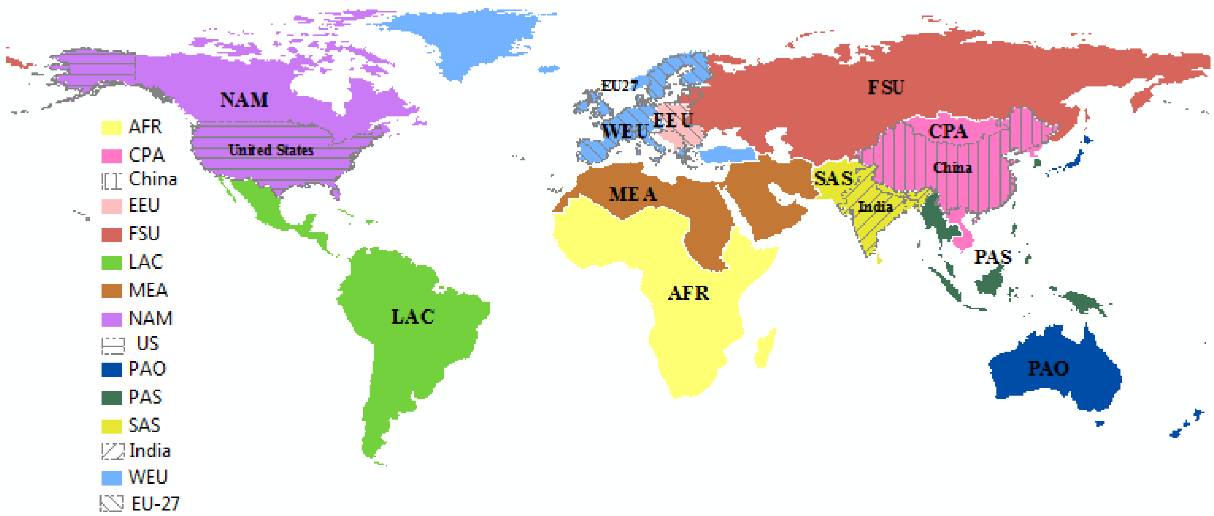



Figure 10. Geographical regions used in BISE model

Within each region different climate zones are considered in order to capture the difference in building energy use and solar energy generation caused by climate variations. The differentiation among different climate zones is based on several climatic factors in terms their influence on building energy demand for space heating, cooling and dehumidification, namely:

- Heating Degree Days (HDD)
- Cooling Degree Days (CDD)
- Relative Humidity of the warmest month[22](RH)
- Average Temperature of the warmest month (T)

NASA climatic data for these parameters were processed by the author by means of GIS spatial analysis tool and raster calculator technique and analyzed with ArcGIS 9.3 software. This multiple-criteria climate classification includes 17 climate zones, where each zone depicts potential energy needs for space heating, cooling and dehumidification in order to provide thermal comfort in buildings (see Figure 11).

[22] July is assumed to be the warmest month for the Northern Hemisphere and January – for the Southern Hemisphere

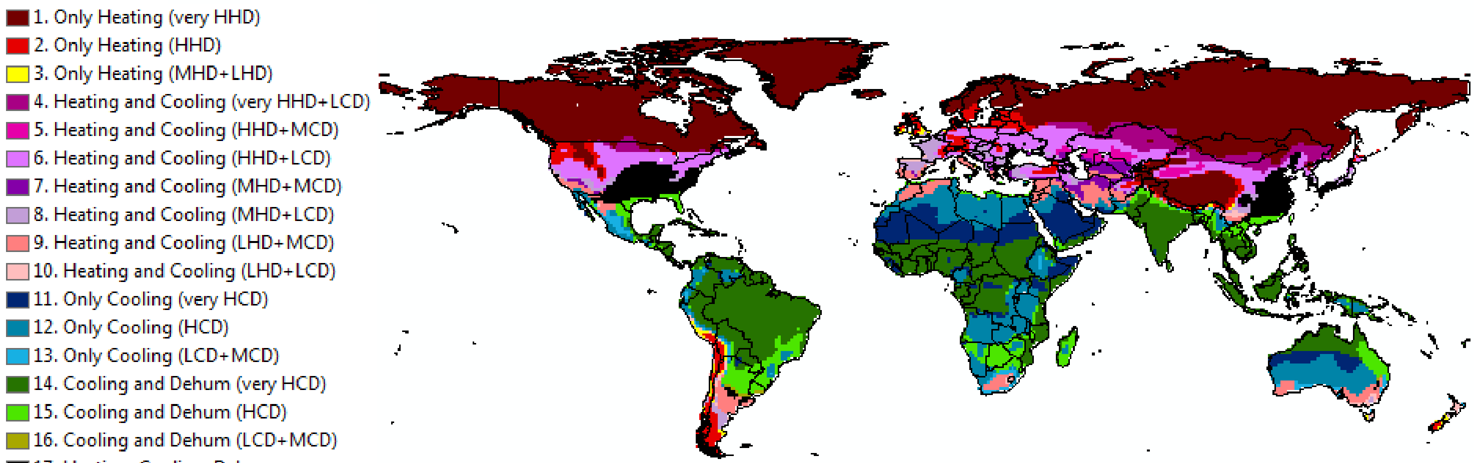



Figure 11. Climate classification from 3CSEP-HEB model

As this climate classification is very novel in its nature and has been elaborated by the author specifically to distinguish among different energy needs in buildings, according to the location and climate conditions, it suits very well the needs of the model presented in this dissertation and is used in the calculation of solar energy potential.

The HEB model distinguishes between urban, rural and slums areas, as well as between residential and non-residential buildings. In urban areas residential buildings include single-family and multifamily buildings, while in rural areas only single-family buildings are assumed. Non-residential buildings include six sub-categories: hotels and restaurants, hospitals, educational, office, retail and other buildings.

The model also takes into account five building vintages in terms of different levels of building energy performance: existing/standard, new, retrofit, advanced new and advanced retrofit buildings.

The same structure of building types and vintages has been adopted for the model elaborated for this dissertation in order to facilitate the comparison between building energy demand and potential solar energy supply from building-integrated solar technologies.

Final energy consumption in HEB model is calculated from the total floor area for a region/country, climate zone, building type with particular building's energy intensity varying among different building vintages, given as kWh/$m^2$year of final energy. Since building floor area is a primary variable, a model for building floor area dynamics is in the core of 3CSEP-HEB mode;.

Building stock model is based on annual dynamics, including the following process: demolition (a certain share of the building is demolished due to the end of the lifecycle or other reasons), renovation (a certain share of the building is renovated) and new construction (certain number of new buildings is added to the economy).

New buildings present the difference between total floor area requirements and the available building stock (existing building stock minus demolished one) for each year.

The procedure for calculating floor area differs for residential and commercial & public (C&P) buildings. Residential floor area growth is based on floor area per capita estimates and population projections for each region or country with the assumptions that the developing world will have approximately the same standard of living in terms living space per capita as OECD countries by 2050. This is then coupled with the urbanization rate to produce a total floor area for rural and urban buildings. The former are assumed to be single-family and the latter are split between single-family and multifamily. Building floor area is also calculated for each climate zone by applying share of population for each climate zone within each region/country. Share of population for each climate zone was calculated by means of GIS analysis through overlaying created climate split with population grid and utilizing a GIS zonal statistics technique.

The main driver for commercial floor area calculation is GDP per capita projections for each region or country. C&P floor area in 2005 is divided by GDP in 2005, which yields "C&P floor area elasticity" (Bressand et al. 2007). This proportionality constant, when multiplied by GDP for a given year gives the C&P floor area demanded by the economy. Since the developing world has a higher ratio of C&P floor area to GDP than the developed OECD countries, the ratio is assumed to decrease over time and eventually achieve an average OECD level of floor area elasticity, representing a shift to higher GDP output per unit floor area synonymous with completed economic development.

In order to calculate building energy use for space heating and cooling floor area is multiplied by specific energy consumption for corresponding regions, climate zones, building types and building vintages. Specific energy consumption values are collected from various sources starting from governmental statistics to data on exemplary buildings reported in academic publications.

The procedure for calculating energy use for water heating is similar with the difference that due to the lack of reported data on energy use for water heating in exemplary buildings, these figures are derived from the data on hot water energy consumption per person (or household or region) per year for different regions and building types, taking into account different technologies, their efficiencies and energy sources.

The model allows for computing energy demand from buildings from 2005 to 2050 as well as for estimating energy use reduction from introducing of ambitious energy efficiency measures resulting in 80-90% decrease in building energy performance for space heating and cooling.

Such a reduction is a necessary step towards NZEBs and is well captured by Deep Efficiency scenario of 3CSEP-HEB model. This scenario presumes a quite ambitious proliferation of energy efficiency best-practices in buildings on world-wide scale. Other scenarios considered in the model include Moderate Efficiency scenario, which accounts for mediocre continuation of the existing policy trends and modest improvements in building energy efficiency in some developed regions, and Frozen Efficiency scenario, which presumes the absence of future political efforts and technological improvements related to building energy efficiency.

Key characteristics of each scenario are briefly described in Table 17.

Table 17. Key characteristics of the three scenarios under 3CSEP-HEB model

| Parameter | Deep | Moderate | Frozen |
|---|---|---|---|
| Main features of final energy use for SH&C | Wide proliferation of building best-practices in construction and renovation | Compliance with national building codes and current enforced energy efficiency policies (e.g in EU – EPBD) | Energy performance of new and retrofit buildings do not improve as compared to their 2005 levels |
| Main feature for water heating energy use | Solar systems and/or advanced heat pumps gain large significance | Water heating efficiency measures are not more ambitious than currently existing programs | The fuel mix and efficiency of water heaters do not change |
| Share of advanced buildings | By 2022 advanced will replace most of conventional new and retrofit buildings on the market | In most of the regions no advanced buildings are assumed, except for (EU, Western Europe and North America) | Advanced buildings assumed only in Germany as 5% and in Austria as 10% of their new building stock; no advanced retrofit buildings |
| Energy performance of advanced buildings | Passive house level (15–30 kwh/m$^2$/yr) | Passive house level (15–30 kwh/m$^2$/yr) | Passive house level (15–30 kwh/m$^2$/yr) |
| Energy performance of conventional buildings | New buildings correspond to regional building codes or averages; retrofit consume 30% less than standard buildings | New buildings correspond to regional building codes or averages; retrofit consume 30% less than standard buildings | New buildings consume 10-20% more than the national building codes or averages; retrofit consume 10% less than standard buildings |
| Renovation rate | Till 2019 – 1.4%, from 2020 – 3% for all regions | Till 2019 – 1.4%, from 2020 – higher level (1.5–2.1%, depending on the region) | Fixed at 1.4% for all regions |
| Policies considered | Strong political efforts are need to encourage such an ambitious market transformation | Current policy trends (e.g. EPBD recast in EU-27 and local building codes in other regions) | No policy interventions |

Source: Urge-Vorsatz, Petrichenko, and Butcher (2011)

In this dissertation the results of Deep scenario are used most often for the purpose of energy balance analysis, as NZEBs usually presume high level of energy efficiency.

### V.1.2 Estimation of building energy demand for lighting and appliances – BUENAS model

Electrical energy uses such as domestic appliances, office equipment and lighting are considered as part of building energy demand and are taken into account in this dissertation for building energy balance calculation. The data on lighting and appliances energy use for different countries or regions have been obtained from existing Bottom-Up Energy Analysis System (*BUENAS*) model.

"BUENAS is an end use energy demand projection model developed by Lawrence Berkeley National Laboratory (LBNL) in the United States of America with support from the Collaborative Labeling and Appliance Standards Program (CLASP), the International Copper Association (ICA) and the United States Department of Energy (USDOE)" (McNeil et al. 2012).

BUENAS allows for modeling energy demand by various types of equipment and aggregating the results by the end use, sector or country (McNeil et al. 2012).

BUENAS covers 11 countries and the European Union (EU-27) modeled as one region. Countries currently included in BUENAS are: Australia, Brazil, Canada, European Union, India, Indonesia, Japan, Republic of Korea, Mexico, Russia, South Africa and the United States. The energy demand for China has been modeled separately (detailed results and methodology are presented in Zhou et al. 2011) and being integrated into BUENAS model (McNeil et al. 2012).

BUENAS covers a wide range of energy-consuming products, which are usually covered by Energy Efficiency Standards and Labeling (EES&L) programs in different countries. There are 16 end-uses currently considered in the model:

- Residential Sector: air conditioning, cooking + dishwashing, fans, lighting, refrigeration, space heating, standby, televisions, water heating, laundry;

- Commercial Sector: air conditioning, lighting, refrigeration, space heating, laundry;
- Industrial Sector: electric motors, distribution transformers (McNeil et al. 2012).

The model does not cover industrial processes and “miscellaneous’ end uses, or end uses not typically included in EES&L programs. Therefore, the model analyzes only major end-uses, which means that the sum of estimated energy consumption for different end-uses for a certain country does not represent the total sector consumption. According to the authors’ estimations, the end-uses included in the model cover over 80% of energy use in the residential and commercial building sectors (McNeil et al. 2012).

BUENAS is a bottom–up stock accounting model, which aims at providing a comprehensive assessment and prediction of energy consumption, energy savings and greenhouse gas emissions reductions from energy efficiency programs for each type of equipment and in each country (McNeil et al. 2013).

National energy demand of each end-use is calculated, according to the following modification of the Kaya identity (McNeil et al. 2012):

$$\text{Energy} = \frac{\text{Activity} \times \text{Intensity}}{\text{Efficiency}}$$

Activity is the size of the stock (number of units), Intensity is the usage and capacity of each unit, Efficiency is the technological performance of the unit, which can be affected by government policies (McNeil et al. 2013).

Energy demand in each scenario is determined by equipment stock, usage, intensity, and efficiency. When available, BUENAS uses sales forecasts taken from country studies to project equipment stock. Otherwise, BUENAS uses an econometric model of household appliance uptake developed by the authors (McNeil et al. 2013).

Two scenarios are elaborated within the BUENAS models differentiated by the level of actions taken: Business As Usual (BAU) and Best Practice Scenario (BP) (McNeil et al. 2012).

Under the BAU scenario the growth in energy demand is driven by growth in both activity and intensity. The key assumption of the BAU scenario for efficiency is "frozen efficiency" trend from 2010 meaning that the efficiency of new products remains fixed on the level of the base year. Exceptions to this take place when projections with 'market-driven' efficiency improvements are available (McNeil et al. 2012).

Activity and intensity projections are assumed equal for all scenarios implying that it is the efficiency of units, which determines the difference in the scenarios' results, as changes in the units' stock and usage patterns are not included in the policy effects (McNeil et al. 2012).

The BP Scenario considers the potential impacts of regulations on the ambitious efficiency improvements achievable for all countries (e.g. removal of low-efficiency models from the market or adoption of best available technologies). The BP Scenario assumes that all countries achieve stringent efficiency targets by 2015. The standards are further improved in the year 2020, assuming that either the same level of improvement is made in 2020 as in 2015 or that a specific target, such as current "best available technology," is reached by 2020 (McNeil et al. 2013).



### V.1.3 Estimation of global and regional building-integrated solar energy potential – BISE model

In pursue of the research aim an independent model – **B**uilding **I**ntegrate **S**olar **E**nergy (**BISE**) model – has been elaborated by the author of this dissertation. It allows for analyzing the potential and trends of solar energy supply provided by building-integrated advanced solar technologies. Being an autonomous tool BISE model uses floor area estimations from 3CSEP-HEB model as input data, in order to develop roof area projections available for solar technologies installations. It is accomplished based on roof-to-floor ratios, acquired through GIS analysis, and availability factors, obtained from the literature.

BISE model aims at estimating the maximum possible technical potential of the building-integrated solar energy generation focusing on advanced solar technologies (PV/T). It is assumed that PV/T technologies are installed on all available roof areas in buildings during construction or renovation starting from the year 2014 and becoming a common practice for all retrofit and new buildings by 2025. Together with ambitious reduction in building energy use through energy efficiency improvement (as assumed by Deep Efficiency Scenario of 3CSEP-HEB Model) the results of BISE model give the opportunity to determine in which locations, climate zones and building types it is feasible to achieve NZE target by utilizing only solar energy.

Another fundamental assumption of the BISE model is that future building-integrated solar energy generation is determined by the building stock dynamics, driven by changes in population, GDP, floor area per capita, processes of demolition and renovation, rather than changes in climatic and meteorological characteristics (which are assumed to be constant). Very detailed NASA climatic data on four parameters (top-of-atmosphere irradiation, global irradiation, ambient temperature, wind speed, etc. – for more details see Section V.3) are used to calculate hourly irradiation on one square meter of a solar system in 2005. This is the key parameter for calculating both solar thermal and solar electric energy supply and assumed constant in subsequent years of the modeling period (as solar activity modeling is beyond the scope of the present research).

BISE model presumes modeling of thermal and electric solar energy separately by using the same hourly irradiation on one square meter of a solar system area, but different parameters for thermal and electric efficiency and different systems' losses.

The uniqueness of BISE model is in providing the opportunity to calculate hourly irradiation on one square meter of a solar system's surface for the whole globe with the precision appropriate for one single solar system. The algorithm utilizes different types of solar radiation, taking into account the tilt of the system (assuming an optimal tilt), earth rotation, latitude, time of the year and position of the sun.

## V.2 Calculation Procedures

To the authors' best knowledge it is the first time when technical potential of building-integrated solar hybrid technologies is estimated on the global scale, benefiting from a comprehensive geo-spatial analysis, energy modeling and hourly data of high resolution.

The BISE algorithm consists of four main parts, which presume the calculation of:

1) Solar system's area;
2) Hourly irradiation on the plane of the solar system's array;
3) Electric solar energy supply;
4) Thermal solar energy supply.

The calculation procedures for each of these parameters are discussed in the following sections.



### V.2.1 Solar System's Area

Here solar system's area is considered as the area of a building's roof occupied by solar technology, from which solar energy can be produced.

There are three main steps, which have to be taken in order to calculate solar system's area.

1. Roof area for each region and climate zone;

In order to calculate solar system's area, first, total roof area (*RA*) of each region is calculated. In order to do this, floor area (*FA*) projections are taken from HEB model for each region, climate zone, building type and year and multiplied by roof-to-floor ratio ($RF_{ratio}$), which varies, according to building type and region (see Section VI.1.3 for more explanation):

$$RA = FA \times RF_{ratio}$$

2. Roof area available for solar systems installation for each region and climate zone

Total roof area for each region and climate zone has been subsequently reduced in order to account for the shaded areas of the roof and the ones occupied by facilities and, therefore, unavailable for the solar technologies installation.

The availability factors presented in Izquierdo et al. (2008) have been applied to corresponding building types in order to account for effects of shading ($AvF_S$) and roof facilities ($AvF_f$):

$$RA_{available} = RA \times AvF_f \times AvF_s$$

Where $RA_{available}$ - roof area available for solar systems installation

3. Solar system area

Available for solar installations roof area is further reduced in order to get the aperture area of a solar system, i.e. the surface of the system, which is directly exposed to solar radiation and through which solar energy enters the system. It is done by means of the aperture factor ($F_{aperture}$) in order to remove the areas between the systems, as well as the systems frames from the consideration:

$$A_S = RA_{available} \times F_{aperture}$$

Where $A_S$ – solar system area

### V.2.2 Hourly irradiation on the plane of the solar system's array

Hourly irradiation on the pane of the solar system is the amount of solar energy received by one meter of the solar system's surface per hour. It is determined by a number of factors, such as the amount of global, beam and diffuse irradiation, the tilt of the solar technology's surface, surface albedo, etc. Several steps have to be taken in order to calculate all the necessary parameters from the available data. The logic of the calculation is notably framed by Duffie and Beckman (1991), RETScreen (2004a), RETScreen (2004b).

4. <u>Hourly Clearness Index (K)</u>

Clearness Index is the ratio of solar radiation at the surface of the earth to extraterrestrial radiation is called the clearness index:

$$K = \frac{I_{glob}}{I_{TOA}}$$

Where $I_{glob}$ - hourly global solar irradiation per $m_2$ (in $W/m^2$/hour), $I_{TOA}$ - hourly top-of-atmosphere solar radiation per $m^2$ (in $W/m^2$/hour).

5. <u>Hourly diffuse radiation</u>

Diffuse radiation is the solar radiation received from the Sun after its direction has been changed through scattering by the atmosphere. Hourly diffuse radiation ($I_D$) is calculated from hourly global radiation ($I_{glob}$) using the following correlation (Duffie and Beckman 1991):

$$\frac{I_D}{I_{glob}} = \begin{cases} 1.0 - 0.09K & for\ K \leq 0.22 \\ 0.9511 - 0.1604K + 4.388K^2 - 16.638K^3 + 12.336K^4 & for\ 0.22 < K \leq 0.80 \\ 0.165 & for\ K > 0.80 \end{cases}$$

These correlations determined by Erbs et.al. (1982) are based on the empirical data collected from four stations in US and one in Australia. The constant value is recommended in cases when the clearness index becomes higher than 0.8, as there are very few data available. According to Duffie and Beckman (1991), there is certain evidence of the increase in the hourly diffuse radiation, as the values of the clearness index grow above 0.8. The authors explain this increase by the reflection of radiation from clouds during times when the Sun is unobscured but when there are clouds near the path from the Sun to the observer.

6. <u>Hourly beam radiation</u>

Beam radiation is the solar radiation received from the Sun without been scattered by the atmosphere. Beam and diffuse radiations are the two components of the global (total) radiation and, therefore, having hourly global radiation as input data and having determined the amount of hourly diffused radiation it is possible to calculate the hourly beam radiation ($I_B$) in a fairly simple manner:

$$I_B = I_{glob} - I_D$$

7. <u>Hourly total solar radiation on the (tilted) plane of the solar array</u>

As solar array is usually titled with a certain slope ($\beta$) it is necessary to calculate the amount of the total solar radiation received by the solar system's surface ($I_T$) , which can be further potentially converted into thermal or electrical energy. $I_T$ includes three main components: beam radiation ($I_B$), diffuse radiation ($I_D$) and the global radiation ($I_{glob}$) diffusely reflected from the ground:

$$I_T = I_B R_b + I_D \left(\frac{1 + cos\beta}{2}\right) + I_{glob}\, \rho \left(\frac{1 - cos\beta}{2}\right)$$

where

$R_b$ is the ratio of beam radiation on the solar array to that on the horizontal surface

$\frac{1+\cos\beta}{2}$ is a view factor to the sky, i.e the proportion of the sky that is visible from a given observer point (surface of the solar array) (Oke 1987)

$\frac{1-\cos\beta}{2}$ is a view factor to the ground; and $\rho$ is the portion of the global solar radiation reflected from the ground.

### V.2.3 Electric Solar Energy Supply

8. <u>Electric efficiency of the solar system</u>

Electric efficiency is significantly determined by the configuration of the solar system and the temperature of the system:

$$\eta_{elec} = \eta_r \times (1 - \beta_p \times (T_c - T_r))$$

Where $\eta_r$ is the solar system electric efficiency at reference temperature $T_r$ and $\beta_p$ is the temperature coefficient for the system's efficiency. $\eta_r$ and $\beta_p$ depend on the type of solar system. $T_c$ is the hourly solar system's surface temperature defined by the following formula:

$$T_c - T_{amb} = (219 + 832K) \times \frac{NOCT - 20}{800}$$

where

*NOCT* is the Nominal Operating Cell Temperature, which depends on the type of the solar system

$K$ is the hourly clearness index

$T_{amb}$ is the hourly ambient air temperature.

The method presented here for calculating electric efficiency has been adapted from Duffie and Beckman (1991), RETScreen (2004a) and Ibrahim et al. (2009). Ibrahim et al. (2009) used similar approach in the calculation of the electric efficiency of a PV/T system.

9. <u>Electric energy output generated by one square meter of a solar system per hour</u>

The amout of captured solar energy by a solar system, which can be transformed into electricity directly depends on the electrical efficiency of the solar system ($\eta_{elec}$) and the amount of total solar radiation received on the solar array ($I_T$):

$$E_{El\ output} = I_T \times \eta_{elec}$$

In BISE model the result of this step is calculated per one square meter of the solar system's surface.

10. <u>Electric energy produced by one square meter of a solar system per hour</u>

Certain portion of the solar energy collected by the solar system is lost during the operation of the technology. In BISE model this amount is accounted as miscellaneous losses and other system losses ($L_{miscel}$) in the following way:

$$E_{El\ prod} = E_{El\ output} \times (1 - L_{miscel})$$

$E_{El\ prod}$ stands for the amount of energy produced by the solar system, which is available for to the load and/or battery[23].



[23] In this study only on-grid systems are considered, therefore, the option for the battery storage has not been modeled

11. Electric energy supplied to the grid by one square meter of a solar system per hour

Another type of losses occurs during the transformation of the solar electricity between different types of currents by the inverter. Therefore, the inverter's efficiency directly influences the actual amount of electricity, which can be supplied to the electrical grid by the solar system:

$$E_{El\ supp} = E_{El\ prod} \times \eta_{inverter}$$

Depending on the grid configuration not all this energy may be absorbed by the grid, therefore, this amount of energy can be further reduced by applying PV energy absorption rate (RETScreen 2004a). This is the amount of energy produced by the PV system that will actually be delivered to the utility. The remaining energy can be available for other uses or wasted because of mismatches between PV output and utility energy demand. As the portion of solar electricity, which can be potentially lost, is rarely higher than 5% and for central-grid connected systems the absorption rate is typically 100% (RETScreen 2005a), this factor has been neglected in this dissertation.

12. Total electric energy supplied by solar systems by region, climate zone, building type

Multiplying the amount of solar electric energy supplied by one square meter of the solar system by total solar system's area ($A_{SolSys}$) calculated in Section V.2.1 gives the total amount of solar electric energy, which can potentially be supplied to buildings of a certain type in a certain region and climate zone:

$$E_{El\ total\ supp} = E_{El\ supp} \times A_{SolSys}$$

### V.2.4 Thermal Solar Energy Supply

This section describes the steps to calculate the amount of hourly total solar radiation received on the plane of the solar array and converted into thermal energy, which can be utilized in buildings for water and space heating.

In PV/T panels the solar energy is converted into heat in the same way as in conventional solar thermal collectors with the actual conversion taking place in the absorber (van Helden et.al. 2004).

13. <u>Heat loss transfer coefficient ($U_L$)</u>

The heat loss transfer coefficient represents the heat losses from the solar system, which occur from the top through the glass cover, bottom and sides, considering convection and re-radiation losses in different directions (Fatigun et al. 2012).

The heat loss coefficient is calculated using the empirical equation proposed by Klein (Yeh and Lin 1996):

$$U_L = \left\{ \frac{N \times T_{pl}}{C \times \left[ \frac{(T_{pl} - T_a)}{(N - f)} \right]^e} + \frac{1}{h_w} \right\}^{-1} + \frac{\sigma \times (T_{pl} + T_a) \times (T_{pl}^2 + T_a^2)}{(\varepsilon_p + 0.00591\, h_w)^{-1} + \frac{[2N + f + 0.133\varepsilon_p]}{\varepsilon_g} - N}$$

where

$N$ – number of glass covers
$C = 520\ (1 – 0.000051\varphi^2)$, where $\varphi$ - latitude
$f = (1 + 0.089h_w – 0.1166h_w\, \varepsilon_p) \times (1 + 0.07866N)$

$e = 0.43\ (1 – 100/T_{pl})$
$h_w$ – wind heat transfer coefficient [W/(m$^2$K)] = $2.8 + 3.0V_w$, where
$V_w$ – wind speed, [m/s] = $\sqrt{(u^2 + v^2)}$, where $u$ - zonal wind component, $v$ – meridional wind component
$T_{pl}$ – mean plate temperature (see discussion in Step 17)

$T_a$ – ambient temperature
$\sigma$ - Stefan–Boltzmann constant

$\varepsilon_p$ - absorber plate emissivity

$\varepsilon_g$ - glass emissivity

14. Heat removal factor ($F_R$)

Heat removal factor is the ratio of the actual useful energy gain to the useful gain that would result if the whole absorbing surface was at the fluid inlet temperature (Afgan, Bogdan, and Duic 2004).

$$F_R = \frac{\dot{m}\, c_p}{A_S\, U_L} \times \left(1 - e^{-F' A_S U_L / \dot{m} c_p}\right)$$

where
$U_L$ - the heat loss transfer coefficient, calculated in Step 13

$F'$ - the efficiency factor that represents the ratio of the actual useful energy gain to the useful gain that would result if the absorbing surface had been at the average fluid temperature
$A_S$ – solar system's area[24], [$m^2$]

$\dot{m}$ – fluid flow rate, [kg/s]

$c_p$ - specific heat capacity, J/kg/°C

15. Thermal energy output generated by one square meter of a solar system per hour

Depending on a system's configurations not the whole amount of $I_T$ can be converted into thermal energy. Therefore, first, the output energy from one square meter of a solar system per hour is calculated ($E_{TH\ output}$), taking into acount the difference between the temperature of the

[24] In this formula 1 $m^2$ of the solar system is used, as the calculation for the total solar system area will be performed at the latter stages of the calculation process

working fluid entering the system and the ambient air temperature and the solar system's characteristics:

$$E_{TH\ output} = F_R \times (I_T \times (\tau\alpha - \tau \times \eta_{elec}) - U_L \times (T_{in} - T_a))$$

where
$F_R$ is the heat removal factor calculated in Step 14
$\tau$ is the transmittance of the cover
$\alpha$ is the shortwave absorptivity of the absorber
$U_L$ is the overall heat loss coefficient of the collector calculated in Step 13
$\eta_{elec}$ - electrical efficiency of the system calculated in Step 8
$T_{in}$ – inlet fluid temperature (see discussion in Step 16)
$T_a$ – ambient temperature.

The method presented here for calculating energy collected by one square meter of a solar system per hour has been adapted from Duffie and Beckman (1991), RETScreen (2004b) and Ibrahim et al. (2009).

16. Inlet and outlet fluid temperatures

Inlet fluid temperature is the temperature of the fluid entering the solar collector. In this dissertation an iterative approach (as opposed to the assumption of a fixed, constant inlet temperature) has been used for estimating the inlet temperature for each hour in order to consider more realistic conditions, when the fluid temperature is influenced by the thermal energy output from the collector and vice versa.

A fixed inlet temperature (at the level of 18°C) is assumed for the first hour of the sunlight. Using this constant the outlet temperature of the fluid leaving from the collector towards the storage tank is calculated, taking into account the thermal energy output from the collector in the end of the first hour. It is assumed that the collector's outlet fluid temperature is equal to the inlet fluid temperature of the storage tank. Taking into account the thermal losses from the storage tank the outlet fluid temperature of the storage tank is calculated, which is assumed to equal the inlet fluid temperature for the collector in the next hour. The described procedure is repeated for each hour, when the hourly total solar radiation on the plane of the solar array is more than zero (i.e. excluding the dark time of the day). The formulas for calculating the outlet fluid temperature of the collector ($T_{out}$) and outlet fluid temperature of the storage tank ($T_S$) are given below:

$$T_{out} = T_{in} + \frac{1}{M\,c_p} \times E_{TH\ output}$$

$$T_S = T_{in} + \frac{1}{M\,c_p}\,E_{TH\ output} \times L_{TH}$$

where

$T_{out}$ – collector's outlet fluid temperature
$T_{in}$ – collector inlet fluid temperature
M – the mass of the water in the storage tank
$c_p$ - specific heat capacity

$E_{TH\ output}$ – thermal energy output calculated in Step 15
$L_{TH}$ - thermal losses from the storage tank

17. <u>Mean plate collector temperature</u>

Mean plate collector temperature is calculated in a similar iterative manner as the inlet fluid temperature (see Step 16), by means of the formula presented below.

It is assumed that in the first hour of the sunlight the mean plate temperature is fixed at the level of the inlet fluid temperature for this hour plus 10°C. Using this constant the thermal energy output is calculated for the first hour, which is used in the formula below to calculate the mean plate temperature for the next hour.  This procedure is repeated for each hour, when the hourly total solar radiation on the plane of the solar array is more than zero.

$$T_{pl} = T_{in} + \frac{E_{TH\ output}}{2\dot{m}\ c_p} + \frac{E_{TH\ output}}{A_s\ h_{ca}}$$

where

$T_{pl}$ - collector mean plate temperature

$T_{in}$ – collector inlet fluid temperature
$\dot{m}$ – fluid flow rate

$c_p$ - specific heat capacity

$E_{TH\ output}$ – thermal energy output calculated in Step 15
$A_s$ – solar system's area[25]

$h_{ca}$ – heat transfer coefficient between the solar cells and the copper absorber, [W/m$^2$ K]

18. Thermal energy supplied by one square meter of a solar system per hour

In order to estimate the amount of solar thermal energy supplied by one square meter of the solar system in each hour ($E_{TH\ supp}$) the hourly thermal energy output ($E_{TH\ output}$) is reduced by different system losses ($L_{TH}$):

$$E_{TH\ supp} = E_{TH\ output} \times (1 - L_{TH})$$

19. Total thermal energy supplied by solar systems by region, climate zone, building type

Multiplying the amount of solar thermal energy supplied by one square meter of the solar system by total solar system's area ($A_{SolSys}$) calculated in Section V.2.1, Step 3, gives the total amount of solar thermal energy, which can be potentially supplied to the buildings of a certain type in a certain region and climate zone:

$$E_{TH\ total\ supp} = E_{TH\ supp} \times A_{SolSys}$$

[25] In this formula 1 m$^2$ of the solar system is used, as the calculation for the total solar system area will be performed at the latter stages of the calculation process

## V.3 Input Data for BISE model

A number of exiting models and calculation methods have been considered in order to elaborate BISE model. The first version of the model was designed to use the Excel spreadsheet based analysis and Microsoft Access as a software platform. That version of the model was using monthly average of key input climatic parameters and a rather simple calculation algorithm. However, during the analysis of the results and relevant literature sources it was determined that in order to achieve appropriate level of accuracy in calculating solar energy output from building-integrated technologies, it is necessary to take into account hourly climatic data of high resolution in order to capture variations in a number of climatic and weather parameters within one day, which directly influence solar technology's performance and the amount of solar energy produced.

In the light of above the BISE model has been significantly upgraded: global hourly geo-spatial data have been obtained from NASA's Science Mission Directorate's web-site, archived and distributed by the Goddard Earth Sciences (GES) Data and Information Services Centre (DISC) (NASA 2012).

Data were downloaded from the online Modern Era Retrospective Analysis for Research and Applications (MERRA) archive for every hour (from 00:30 till 23:30) of every day of the five years (2001 – 2005) for the following parameters: global irradiation (surface incident shortwave flux), top-of-atmosphere (TOA) irradiation (TOA incident shortwave flux), surface albedo, air temperature at 2m above the displacement height, northward wind speed and eastward wind speed[26]. Figure 9 shows that these parameters are the most crucial for the overall research design.



[26] Northward wind speed and eastward wind speed represent two components of the wind, which have to be taken into account in calculating the overall wind speed (see Section V.2.4, Step 13)

A complete dataset for each parameter includes 43,800 observations (24 hours x 365 days x 5 years). Each file of the size about 50 Mb contains data for one day of the month, therefore, 1,825 (365 days x 5 years) files were downloaded for each parameter (i.e. 1,826 files x 7 parameters = 12,775 files).

For each of the seven parameters an average across the outlined years was calculated (for each month, day and hour) resulting in the profile for an 'averaged' year.

Performing the analysis on the hourly scale has significantly increased the complexity of the model. Thus, a custom-made software platform has been developed in order to efficiently deal with such a big amount of data. With the help of a professional software developer a software platform for BISE model has been elaborated, which allowed for implementing all of the calculation steps presented above with the opportunity to visualize input data and each step of the algorithm in colorful maps with a global coverage, as well as to obtain the numerical results for each region, climate zone and building type. Such a solution has significantly facilitated the process of monitoring the calculation process and tracking possible errors and mistakes, and, consequently, enhanced the robustness of the model's results.

The variation in the above-mentioned parameters for the same hours within one month is not very significant; therefore, an option to aggregate the data for a "typical day of the month" has been incorporated into the software solution in order to decrease the computation time. It effectively reduces the number of observations to 288 (24 hours x 12 months) for the averaged year, without compromising the precision of the results. The aggregation for a typical day of the month is done in the end of the calculation process (and are done in order to decrease the size of the database, which stores the data as well as increase the computation time of the subsequent calculation steps): all calculation steps, which provide the results per one square meter, are performed with original hourly data and only before multiplication by the total available roof area for a certain building type, climate zone and region, the results of the previous steps are aggregated for each hour of a typical day of the month. The aggregation process takes about 2 hours for each month.

The software also allows for visual observation of the data/results dynamics by hour within any selected day of the year, as well as for a typical day of every month. The final results of the calculations (i.e. thermal and electric solar energy output and available roof area for each building type, climate zone and region) are stored into the database supported by Microsoft SQL Server[27].

Figure 12 - Figure 19 demonstrate visualized input data for selected input parameters covering the world for the 1st of January and the 1st of July, 2005 for six selected hours of the day (1, 5, 9, 13, 17 and 21, GMT time).



[27] Microsoft SQL Server is a cloud-ready information platform that will help organizations unlock breakthrough insights across the organizations and quickly build solutions to extend data across on-premises and public cloud (http://www.microsoft.com/en-us/sqlserver/product-info.aspx)

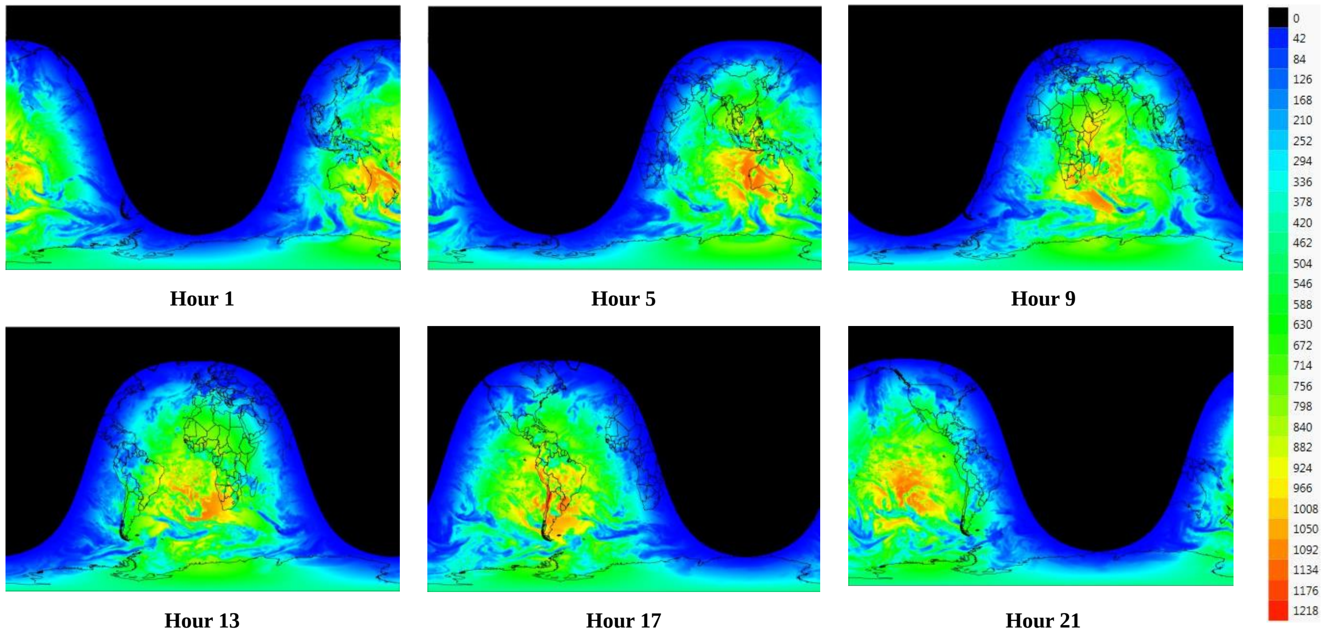



Figure 12. Global solar irradiation (W/m$^2$) for the world for selected hours (GMT time) of January 1st, 2005

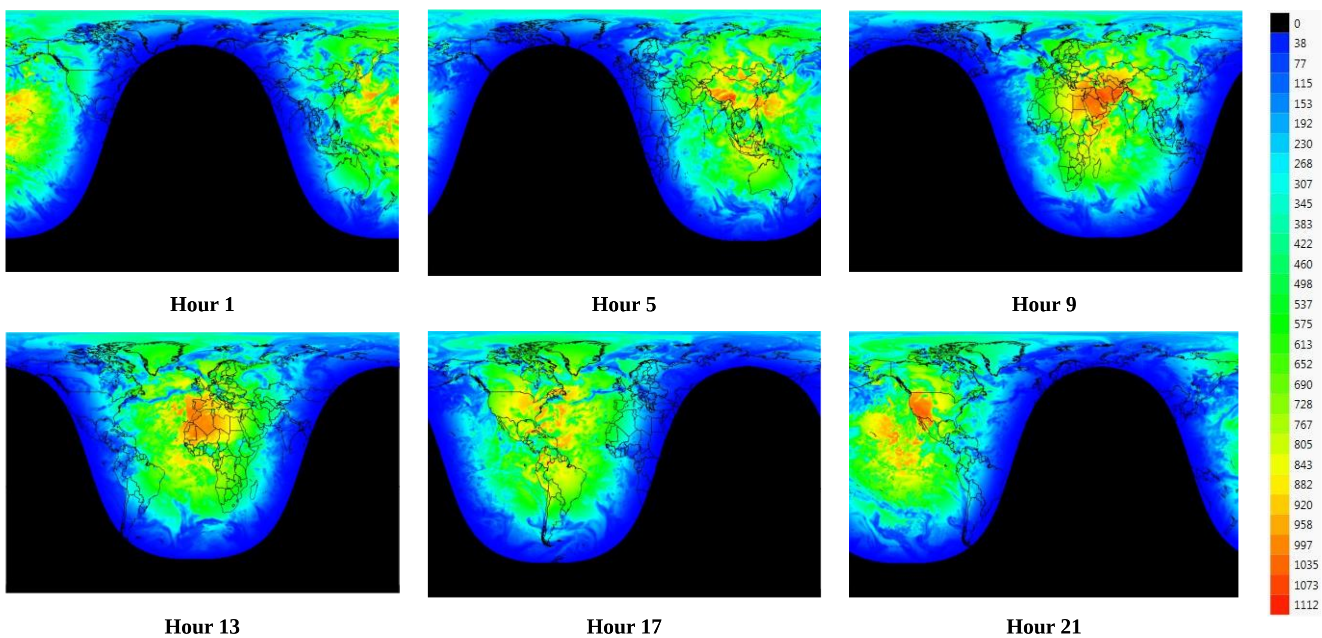



Figure 13. Global solar irradiation (W/m$^2$) for the world for selected hours (GMT time) of July 1st, 2005

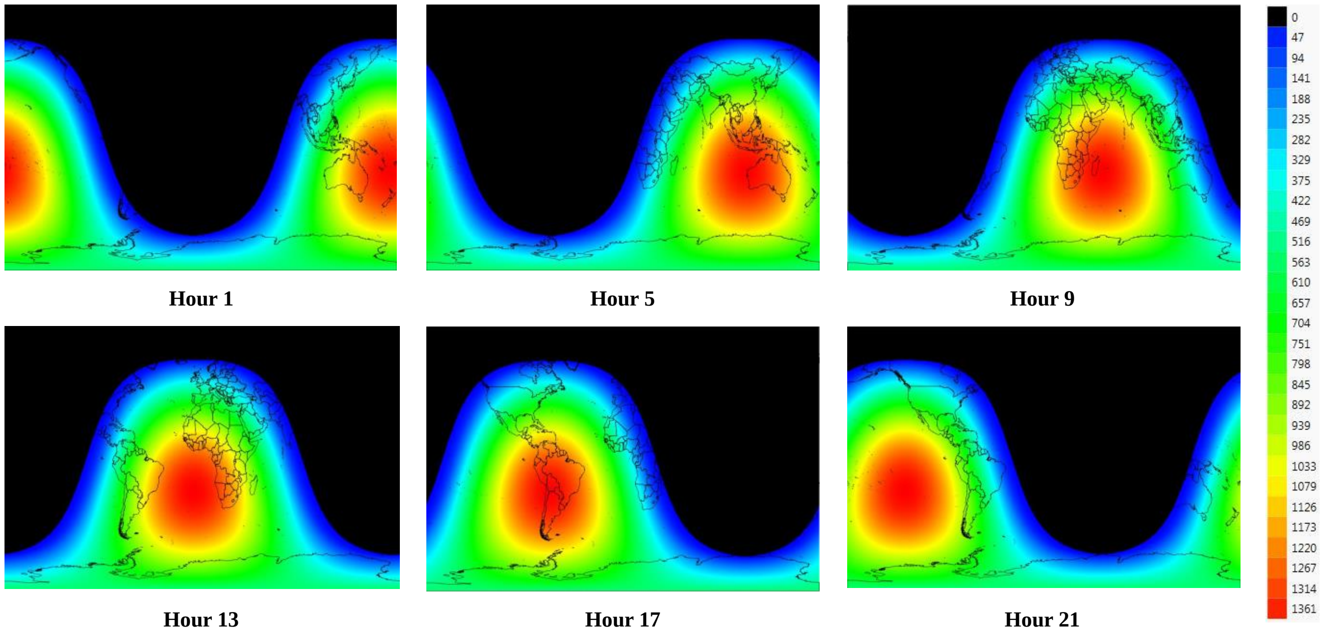



Figure 14. Top-of-the-atmosphere irradiation (W/m$^2$) for the world for selected hours (GMT time) of January 1st, 2005

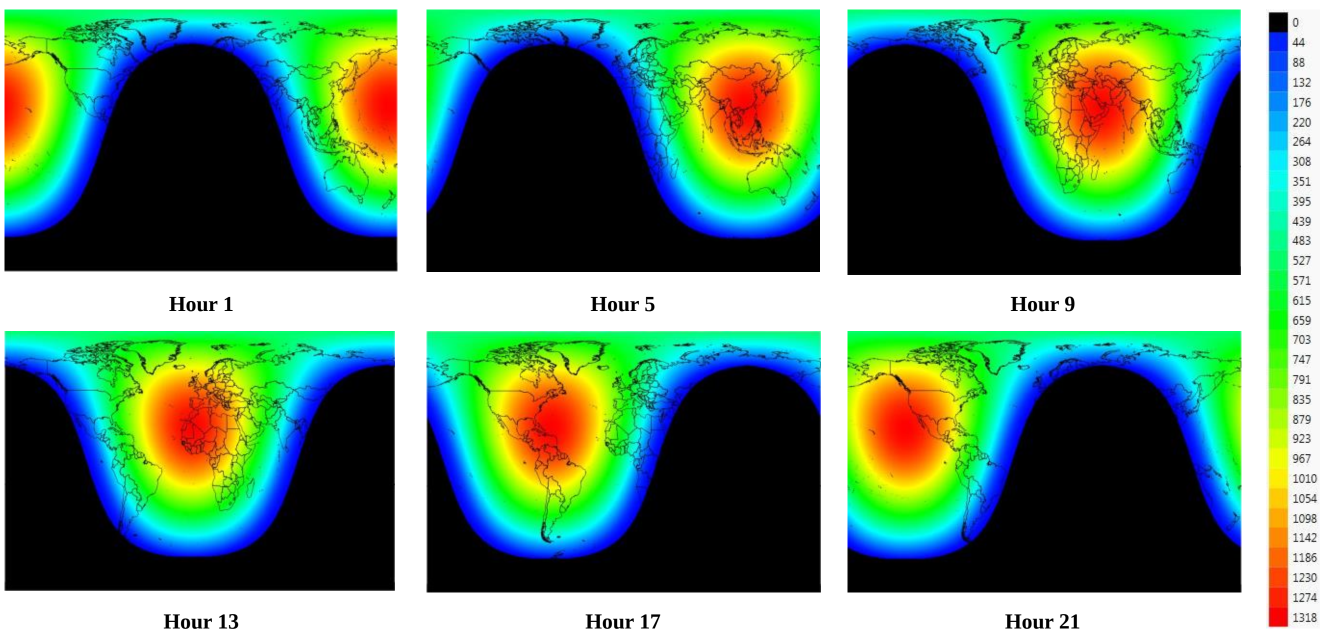



Figure 15. Top-of-the-atmosphere irradiation (W/m$^2$) for the world for selected hours (GMT time) of July 1st, 2005

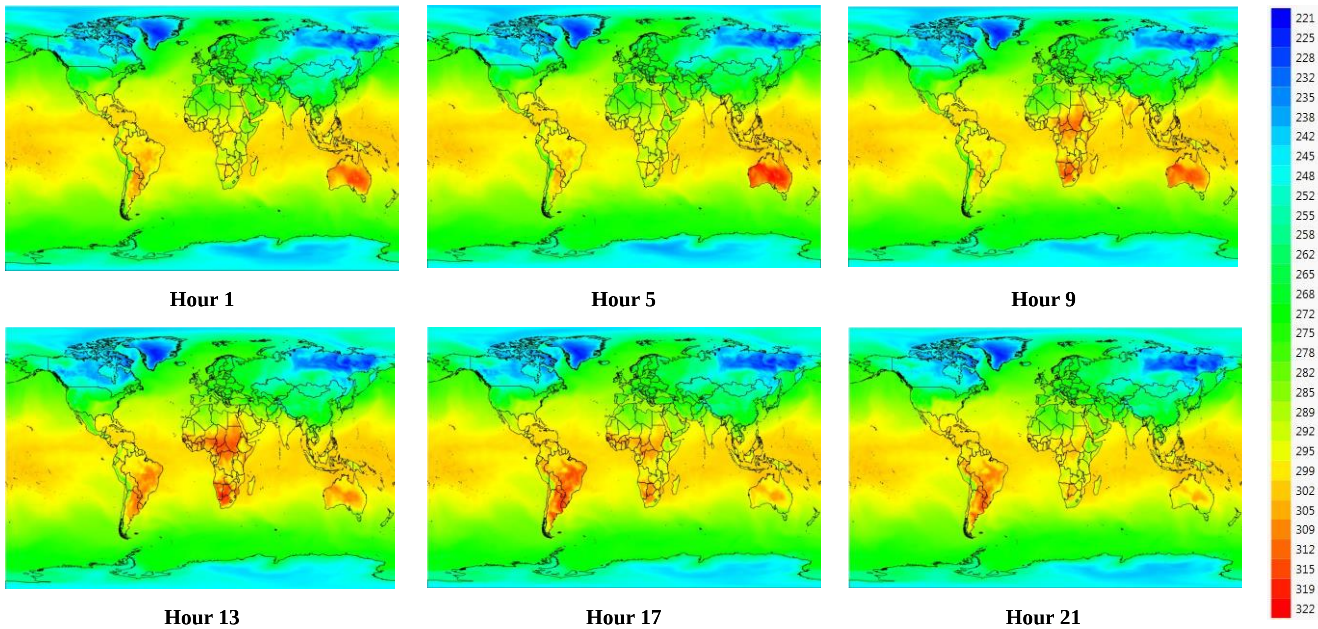



Figure 16. Ambient air temperature (K) for the world for selected hours (GMT time) of January 1st, 2005

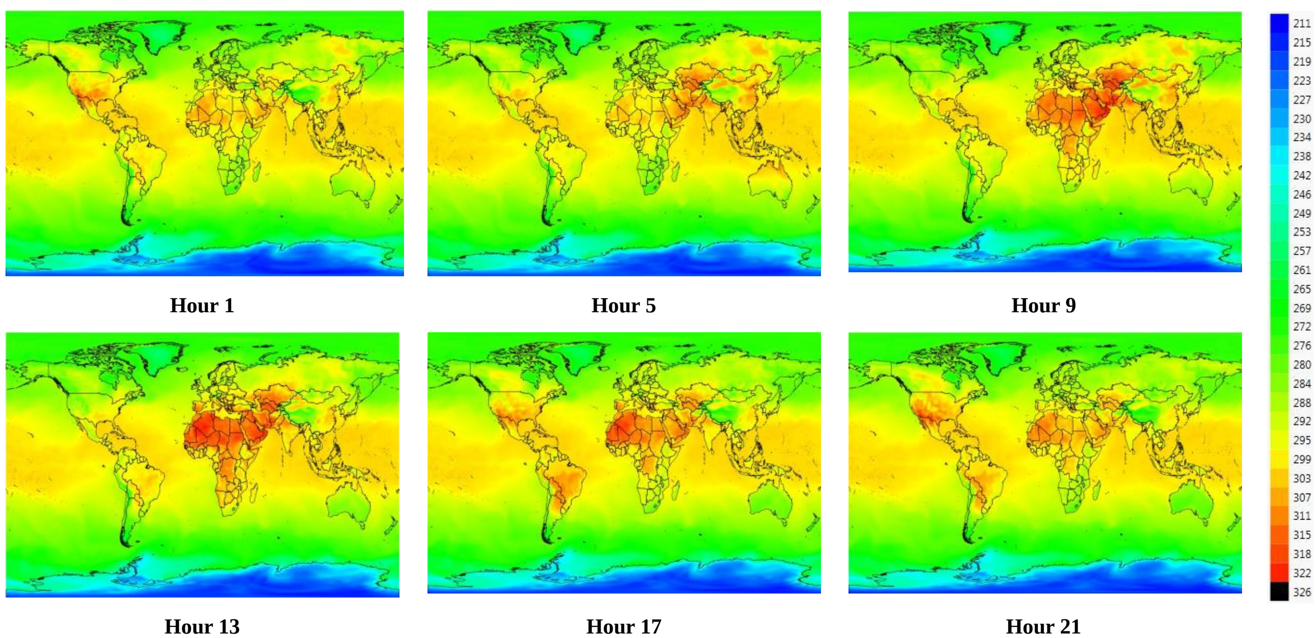



Figure 17. Ambient air temperature (K) for the world for selected hours (GMT time) of July 1st, 2005

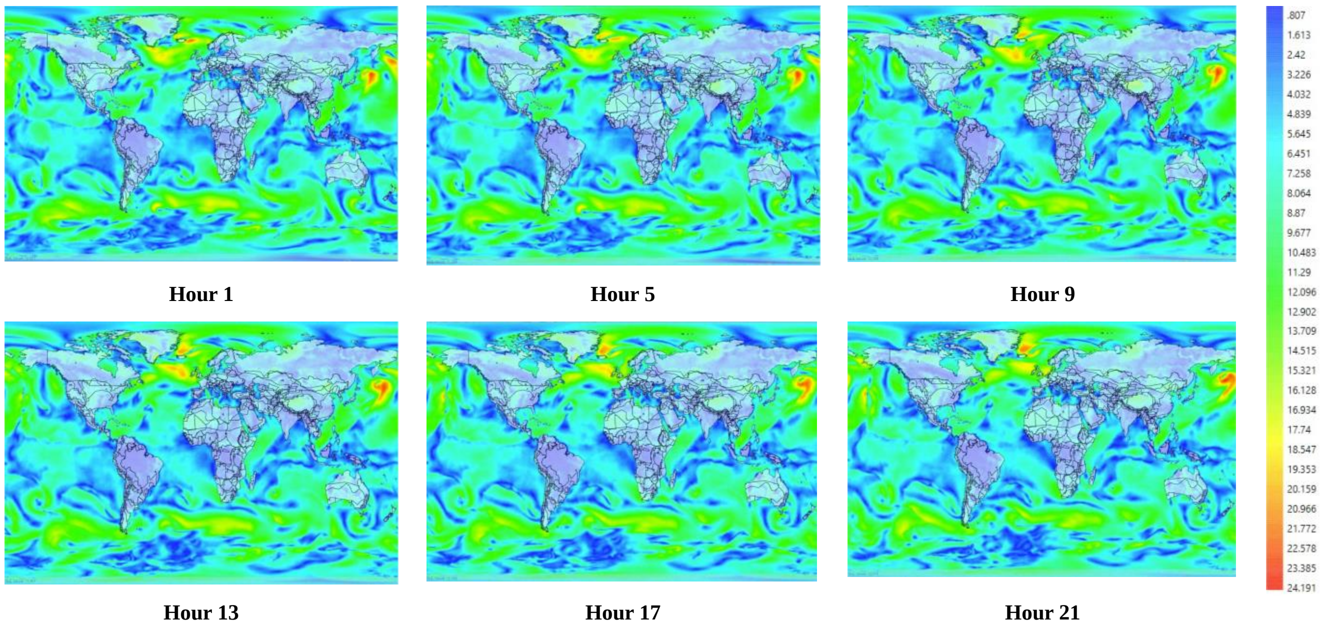


Figure 18. Wind speed for the world for selected hours (GMT time) of January 1st, 2005

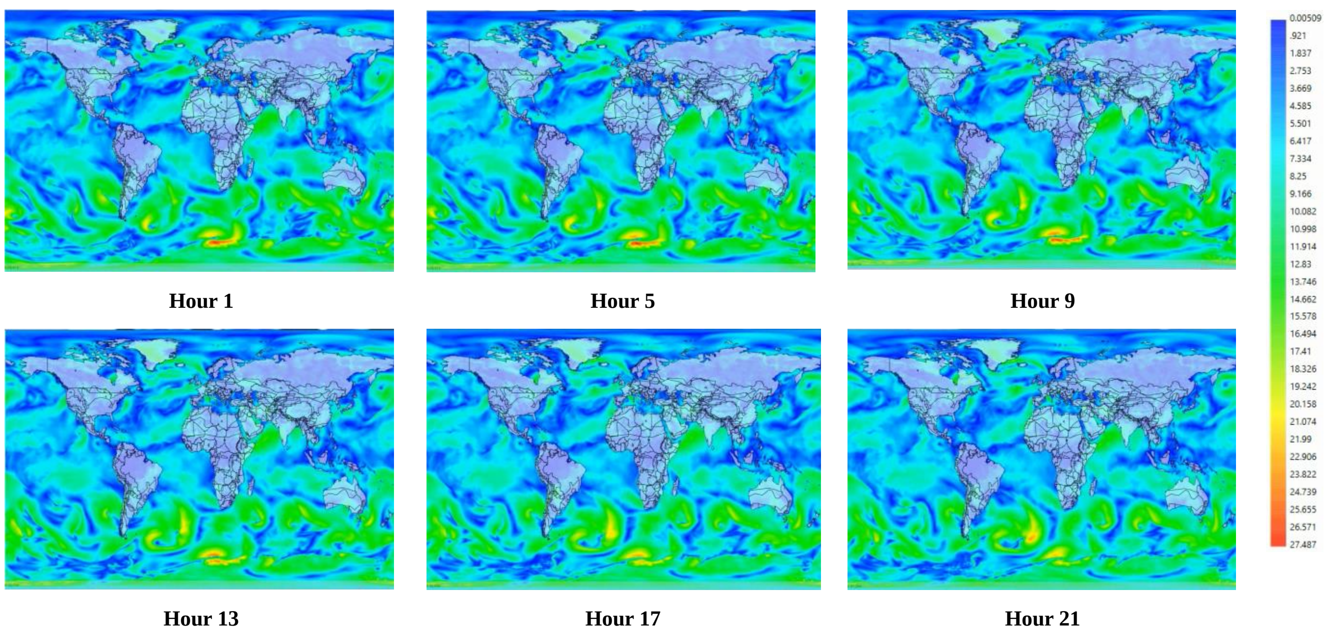


Figure 19. Wind speed for the world for selected hours (GMT time) of July 1st, 2005

## V.4 Research limitations and directions for further research

This section identifies the key limitations of the performed research work as well as discusses certain ways of overcoming them.

The research was limited in time and resources and, therefore, its scope had to be narrowed down, which left out a number of interesting and important topics beyond the boundaries of this dissertation. To the author's best knowledge it is the first study, which attempts to model solar energy potential in buildings on the global and regional scales at the level of sophistication comparable to the models for individual buildings. Global and regional scale, however, requires some compromises in terms of disregarding certain variations and details.

Many of limitations were overcome during the methodology design stage, however, it resulted in the increased complexity of the developed model and calculation time. In order to avoid further overcomplicating, certain assumptions had to be made.

One of the factors with the strongest impact on the robustness of the results is the input data. For this dissertation the data was collected from different sources. As it was not always possible to obtain data at the level of required detail and consistency with the research assumptions certain modifications and, in some cases, compromises were made.

Limitations of the presented PhD research are divided into four main groups, which are discussed in the sub-sections below in more details.

### V.4.1 Limitations related to the research scope

As was noted above, the research presented in this dissertation focuses only on the building-integrated solar energy technologies and evaluates the role of solar energy potential for achieving NZE goal in buildings. This choice was made, as this type of renewable energy sources is the most common for net-zero energy buildings. Taking into account the level of complexity of the presented model, it would not be possible to analyze other types of renewable energy sources at the same level of sophistication within the PhD timeframe. For future analysis the author notes the importance to analyze the potential for utilization of geothermal and wind energy in buildings.

With a similar logic only hybrid PV/T technologies were considered in this dissertation. There is a number of the solar energy technologies currently available at the market. It is not the purpose of this dissertation to compare their performance and analyze engineering details for each of them. The main idea of the presented analysis was to estimate maximum possible and feasible technical potential of the advanced solar technologies. Hybrid PV/T technologies were considered as a logical choice, as they have a number of advantages in comparison to stand-alone systems, as discussed in Section III.3. As possible direction for further research, it would be important to explore the potential of combining PV/T and PV technologies with heat pumps, which can be used both for heating and cooling, depending on the climatic conditions and building energy needs. Prospective of solar cooling seems also very promising to the author, especially in hot climates, where solar thermal energy system tend to produce excessive amounts of heat, which can be further utilized in buildings.

This study focuses on building-integrated solar technologies and, therefore, does not consider the opportunity to produce and import renewable energy beyond building's boundaries. As was presented in Section II.1, often definitions of NZEBs allow for accounting in the building's energy balance for renewable energy produced outside the building's site. For the presented research, however, it was decided to draw the research boundaries around a building and consider it as potentially self-sufficient system, in which energy can be both consumed and produced. The option to extend the research boundaries to the level of a district or community can be interesting for further research, as this level may involve buildings with different heights, geometries, orientations, shading, etc., and, therefore, with different solar energy potentials. It can give the opportunity to utilize solar energy overproduced in certain buildings in those ones, where solar energy supply is insufficient to cover building energy needs.

Present study focuses on the estimation of global and regional technical potential for advanced solar technologies, however, it does not analyze its costs. The author shares the view that the economic analysis of realizing solar energy potential in buildings is a very important exercise. However, the cost data, especially for relatively young PV/T technologies, is very scarce. Moreover, in a number of regions this type of technology is not available on the market yet. Therefore, a robust assessment of the economic potential will require significant time and resources, especially on collecting the data for all world regions and elaborating methodologies for cost transfer and approximation to fill existing data gaps. It may require the level of efforts sufficient for another PhD research.

### V.4.2 Limitations associated with the scale

In this sub-section the term 'scale' includes geographical coverage of the research (world and 11 regions), timeline for the projections (2005-2050) and time period, based on which the results are analyzed (month vs. year).

The present research offers analysis for the globe and 11 big regions. Such an approach has certain advantages and disadvantages. On one hand, it provides a big picture, presents global and regional trends, looks at the possibility for solar net-zero energy future in different locations and under various conditions. On the other hand, as any global model the analysis presented in this dissertation is based on a number of assumptions, which are very often unified for all or a number of regions. It reduces the accuracy of the results (it is the essence of the model to simplify reality and omit certain amount of the details) and simplifies regional variations and peculiarities to a certain extent. The author acknowledges the importance of region-, country- and even city-specific information. Significant attempts were made to collect data for energy use in different regions, however, it was not feasible to go to a deeper level of detail, as it would increase the complexity of the model substantially. Geospatial approach followed by BISE model for obtaining data and calculating solar energy output reduces the significance of this limitation, as it deals with the climatic data of quite high resolution. However, for the purpose of the data analysis and result presentation these data are aggregated for large regions. Another way to capture regional features in the present research was to consider different climate zones and different building types in the analysis.

Solar energy output strongly depends on the weather and climatic conditions, which may vary significantly from one day to another and sometimes even during the day. Therefore, very often solar energy output is analyzed on the hourly basis. BISE model deals with hourly input data and calculates solar thermal and electric outputs at this time scale. However, results on energy use, which are coming from 3CSEP-HEB and BUENAS models, are provided on the annual basis. As described in Sections VII.2 and VII.3 certain assumptions and modifications had to be made in order to derive monthly estimations for energy use from the annual ones.

Most of the results presented in Chapter VIII are analyzed on the monthly basis. In order to discuss the necessity of the solar energy storage, further disaggregation was made to estimate daily results for one month of the year (see Section VIII.5). Data on the hourly solar thermal and electric output for thermal and electric solar energy were calculated by BISE model directly (for this purpose a separate database was created, allowing for the storage of the daily results without performing the aggregation for a typical day of the month), while daily results for the energy use for different end-uses were estimated from the monthly values, based on certain assumptions. Assumptions made for estimating monthly and daily values of energy use presume certain loss of the information, especially for the end-uses, for which an even distributions of values among the months and/or days was assumed (i.e. appliances, hot water, etc.).

Further disaggregation of the daily values into hourly estimates was considered unfeasible, as it would require application of additional assumptions, including selection of a typical daily energy use profile for different building types (and probably different regions), which is accompanied by even higher level of uncertainty.

Another limitation is related to a rather long modeling period used in this study. 2050 time horizon is associated with high uncertainty in relation to both technological and policy development. It is not possible to predict how solar technologies are going to develop in terms of changes in the efficiency and other technical characteristics of the systems. Market development and potential proliferation of solar technologies offer even less transparency. However, 2050 is considered as an important planning period for policy development, which is often accepted in other modeling studies.

### V.4.3 Limitations related to the input data

The input data plays important role in any modeling exercise and to a large extent determines the accuracy of the results. This study uses results on the energy use from other models as the input data and, therefore, certain limitations associated with calculating those results in other models were inherited to some extent.

For example, BUENAS model considers only a limited number of appliances, especially in the commercial sector. Only the results of the business-as-usual scenario were available from this model, which does not match to the ambitious energy efficiency improvements to full extent. Moreover, BUENAS model has different geographical scope from BISE model, which also

Another limitation is related to different modeling period used in BUENAS model. As the period utilized in this study is longer (2005-2050) than in BUENAS model (2010-2030), its results had to be approximated for the following periods: 2005-2009 and 2031-2050. This approximation followed the trends observed in the results between 2010 and 2030 (for more details see Section VII.3). If for the period before 2010 such estimations are likely to be close to the reality (as it is a rather short period from the past), calculations for the period after 2030 are associated with much higher uncertainty. Technological and policy developments for such a long time horizon are quite ambiguous. However, it is unlikely that a pure business-as-usual path will be followed and the current trends will continue without notable technological and/or policy improvements in the future. Therefore, the results for appliances and lighting are likely to be overestimated by the end of the modeling period.

The author is aware of these limitations, however, as precise estimation of electrical load for appliances and lighting was not the primary goal of this study and the data from BUENAS model are mostly used for the purpose to illustrate the possible level of magnitude for buildings electricity consumption rather than analyze exact values, this level of uncertainty was considered acceptable. Moreover, in order to mitigate possible distortions in the results caused by these data, a special focus is made on the sensitivity analysis of energy intensities for lighting and appliances (see Section VIII.5).

Integration of the results acquired from 3CSEP-HEB model was accompanied by much lower level of uncertainty due to similar structures of 3CSEP-HEB and BISE models, in terms of regions, time period, climate zones, building types and building vintages. However, as for BISE model it is important to analyze space heating and cooling separately, certain modifications had to be performed with the data from 3CSEP-HEB model. Its annual estimates joint for space heating and cooling were spread among months and divided between heating and cooling based on the calculated number of the heating and cooling degree days (HDD and CDD) for each month (see Section VII.2). It can be argued whether this method is the best way to calculate monthly energy use for space heating and cooling. Due to the fact that energy use modeling is not a primary research aim of the current work, as well as taking into account lack of more reliable data on building energy use separately for space heating and cooling with the global coverage or absence of a more precise method for calculation, which would not require substantial resources for data collection and modeling, HDD and CDD were considered as an appropriate proxy.

### V.4.4 Limitations associated with the selected calculation method and assumptions

One of the greatest advantages of BISE model is combination of a large scale (i.e. global and regional coverage) with a rather detailed methodology, which to a great extent follows the calculation logic for an individual building. However, global and regional scales presume a great variety of buildings and not always can account for different characteristics, dynamic trends and building geometries. Therefore, some of the parameters had to be assumed fixed or the same for different building types.

For example, a number of system-specific parameters (e.g. absorber plate emissivity, flow rate, efficiency factor, system losses, reference temperature of the system, reference efficiency of the PV part, etc.) were defined based on the typical values found in the literature (see Sections VII.1.2 and VII.1.3). Combination of these parameters characterizes one particular type of the system, which was assumed in BISE model for all locations. In practice there is a number of different types of PV/T systems, which can be utilized in different buildings and different climates in order to optimize the solar output. BISE model does not allow for this kind of optimization, as such detailed calculations do not seem feasible on the global scale. Moreover, being a tool for solar potential estimation BISE model does not aim at serving as an engineering model for testing and evaluating the performance of different solar technologies. However, the interpretation of the results (see Chapter VIII) often includes discussion on alternative or complementary technologies for a particular region and/or building type.

It was assumed that solar systems are installed with an optimal tilt angle, which depends on the latitude (see Section VII.1.1). It is a quite ambitious assumption, which is unlikely to realize in practice especially in retrofit buildings. Although the assumption to have different tilt had been considered, it would have required much more complex methodology from the technical point view as well as more detailed data, which would have been hard to obtain on the global scale. Moreover, optimal tilt angle is one of the conditions to achieve maximum possible solar energy output, which is the primary interest of this work. However, in order to mitigate the possible overestimation of the solar potential a limiting factor was introduced, which reduces solar energy output by 20% for retrofit buildings.

Another limitation is that both thermal and electric efficiencies of the system are assumed to be fixed during the modeling period. Although it may be considered unrealistic due to technological developments in solar technologies, these developments are very uncertain, especially when they have to be translated in exact numbers and assumptions and particularly for the long-term period. Hybrid PV/T systems are already very advanced technologies, which are relatively recent on the market and it is very difficult to find sufficient data to justify the assumptions on the change in their efficiency in the future.

# VI CHAPTER. ROOF AVAILABILITY MODELING AND RESULTS

As it is shown in Section V.2, the first step in the BISE model is the calculation of the roof area available for the building-integrated solar technologies installations. This chapter describes approaches to estimating roof area available for solar energy technologies installation existing in the literature, as well as presents the methodological approach utilized in this dissertation and regional results for total roof area and roof available for solar energy technologies installation.

## VI.1 Approaches to estimating roof availability for solar technology's installation

Estimation of the building roof available for the solar systems' installation in each region and building type is a key step of the BISE model. A number of studies have been investigated in order to determine the most appropriate approach, which would serve this purpose.

The approaches for estimating roof area available for the solar technologies found in the literature can be divided into two main categories, which in this dissertation are called as: (1) geospatial and (2) relational.

The former approach includes the studies, which use methodologies based on GIS analysis and related techniques. Such methodologies usually presume the analysis of detailed cartographic information and/or satellite images of the analyzed territory. Although the results of such studies are often very robust, their methodologies are usually applicable to limited geographical area (a part of the county, a city or even a district), as the detailed GIS data are frequently unavailable for many locations of the world. GIS analysis for larger territories requires substantial resources in terms of time, experts, comprehensive software solutions, etc. It often uses sampling (i.e. conducting the analysis and obtaining the results for a small, limited territory) with subsequent extrapolation of the results to a larger territory (e.g. the country). While such an approach can work well for a homogeneous country or region, it may cause difficulties when applied on the global scale, as it will require numerous sampling in order to capture the diversity of different regions. Therefore, such an approach is unlikely to be applicable for the global analysis.

The latter approach is based on establishing different kinds of relations between the desired output (i.e. estimated roof area available for solar technologies installations) and various influencing factors, data for which are available or can be estimated (e.g. population, GDP per capita, floor area, etc.). This approach requires introducing a substantial number of assumptions, however, it can be used for a wider range of regions, depending on the data availability.

Some examples of the studies within each approach are briefly discussed below.

### VI.1.1 Geospatial approach for estimating available roof area

The methodology used in Izquierdo et.al (2008) and Izquierdo et al. (2011) is based on statistically representative stratified-sample of vectorial GIS maps of urban areas. The key concept of the methodology is the representative building typology (RBT) of the geographical unit. RBT was determined according to two parameters: the population density and the building density and, therefore, a given RBT is defined as a pair of these two densities. 16 RBTs were determined by the authors and the built-up area was derived for each of them through calculating the fraction of the surface area occupied by buildings within the urban area by vectorial GIS samples of the Spanish cadastral database.

The available roof area was computed from the built-up area by applying the following usability factors for each RBT:

- the void fraction coefficient to account for the voids and recesses in buildings;
- the shadowing coefficient account for the shadows generated by other buildings, objects, or the roof's configuration;
- the facility coefficient to account for the surfaces, unavailable due to other specific applications (Izquierdo et.al 2008).

The authors provide the numerical results for each usability factor and each RBT.

Wiginton, Nguyen, and Pearce (2010) also used sampling technique to estimate roof area available for PV installations. They focused their analysis on the region in southeastern Ontario. The authors divided the region into administrative units, which were used as the sampling units. The roof areas wee obtained for 10 of them through automated feature extraction techniques (an object-specific image recognition software available as an extension to ArcGIS) from roof print shapefiles available at some municipalities. For each administrative unit roof per capita was calculated, which allowed for determining an approximate value of roof area per capita for the entire region. This roof area per capita value was multiplied by the total population in the region resulting in the total roof area. Certain reducing factors are applied to the total roof area in order to calculate the available roof area for PV installation. The considered factors account for shading, other roof uses, insolation patterns and building orientation in various combinations and the values are assumed based on several other studies.

The strategy presented in Bergamasco and Asinari (2011) for assessing the roof area available for PV installations in Piedmont Region (Italy) was grounded on the GIS analysis of the complete cartographical dataset for the entire region. The municipality is considered the smallest unit for the GIS analysis, which deals with the shapefiles containing the polygons representing the administrative limits of each municipality. Based on these cartographical data, the number of residential and industrial buildings per municipality and the total roof surface were derived.

The transition from the total to roof area to the area available for PV installations was performed by applying "empirically found cutting coefficients" determined through the visual inspection of Google Earth images. Three main factors were used in the roof availability calculations:

- roof-type coefficient (to account for the areas unavailable due to the roof's configurations);
- corrective feature coefficient (to account for other necessary installations on the roof);
- corrective solar-thermal coefficient (to account for the area, which can be occupied by solar collectors);
- covering index coefficient (to account for the necessary space between PV modules to avoid shading);
- shadowing coefficient (to account for shading from neighboring buildings) (Bergamasco and Asinari 2011b).

Ordóñez et al. (2010) used statistical construction and digital urban maps obtained from Google Earth in order to estimate useful roof surface areas for PV installations in Andalusia. The authors considered a number of the factors influencing the availability of the roof space, such as, building type, orientation, roof tilt angle, location, shading, as well as other competing uses, for example, air conditioning and heating installations, elevator shafts, roof terraces, or penthouses. The authors selected a representative sample of the population under study, living in the residential buildings. This sample was used to calculate the available roof surface area for the analyzed area from urban maps obtained from Google Earth, exported and scaled with the AutoCAD software. As a result the results on the following parameters were obtained: the roof surface area, the surface area of elements that could interfere with the photovoltaic system, the shaded area, and the surface occupied by other installations (e.g. HVAC, elevator shafts, antennas, etc). The authors also account for the share of solar irradiation lost due to shading provided by other roof elements through developing the profile of the obstacles on the roof, which are located in the sun arrays' trajectories during the year (Ordóñez et al. 2010).

Hofierka and Kaňuk (2009) developed a 3-D city model implemented in a geographic information system (GIS) in order to estimate photovoltaic potential in urban areas of the city of Bardejov in Slovakia. A 3-D city model was created based on a digital elevation model and building models with attributes influencing the utilization of solar energy. It required substantial work on collection and processing of detailed geospatial data:

- Collection of hardcopy and digital data including topographic maps, orthophotomaps and large-scale city maps
- Identification and delineation of building footprints from available maps using GIS tools
- Field mapping focused on building morphology and solar-related roof attributes.
- Production of a digital surface model of the area that includes digital elevation model and building surfaces
- Identification of urban zones according to building morphology and functionality (Hofierka and Kaňuk 2009)

Highman (2011) presents the methodology for estimation of roof-top solar potential in the city of Bristol through development of the city solar maps. The analysis is based on detailed LiDaR data for 2011 at a resolution of two points per m$^2$, covering the Bristol City area, and the insolation (kWh/m$^2$yr) data calculated for each data-point, taking into account the position of neighbouring points/surfaces and characteristics of the sun over the year. Areas suitable to solar generation were identified with a using a minimum insolation threshold of 880 kWh/$m^2$yr. Mastermap building footprints tool was used in order to cut building rooftops out from the surroundings. The developed city map allowed of the creation of the database, with an entry for each building. The model also accounted for shading of the rooftops, and any building with unshaded roof space below 10$m^2$ for solar PV was considered unsuitable. Following the described approach approximately 240,000 building rooftops were analysed (Highman 2011).

### VI.1.2 Relational approach for estimating available roof area

Lehmann and Peter (2003) presented the approach to the assessment of roof and facade potential area for solar installations in Europe through formulating a mathematical description of the correlation between solar usable areas and population's density in the region.

The key assumption of this methodology is that building and living structures in Western European countries primarily depend on local population's densities. The authors applied a factor of 0.9 for roofs and 0.66 – for façades to consider losses due to non-usable fractions of the areas and shadowing. They present the results of the determined correlations both for roof and façade areas of residential and non-residential buildings for each Member State of the EU-15 (Lehmann and Peter 2003).

IEA (2002) provides the methodology for evaluating of Building Integrated Photovoltaic (BIPV) potential in Europe. The calculations were based on the transformation of the ground floor area figures into roof and façade surface figures for a certain number of case studies. The data analysis for these case studies allowed for creating "rules-of-thumbs", i.e. availability factors, to derive the suitable roof-top and façade area from ground floor area per capita required for buildings. These rules-of-thumbs accounted for the orientation, morphological and architectural aspects of buildings.

The BIPV potential wss calculated by subsequently applying the factors for solar yield and architectural suitability to the gross roof and façade surfaces. Architectural suitability accounted for the corrections for limitations due to construction, historical considerations, shading effects and use of available surfaces for other purposes. Solar suitability took into account the relative amount of solar radiation for the surfaces depending on their inclination, orientation, location, and the potential performance of the PV system. Solar-architectural suitability was expressed in relative terms and resulted in certain utilization factors. Factors for deriving roof and façade surface areas from the ground floor area were determined based on the analysis of representative samples with a limited number of buildings and section of a particular building stock, and subsequent extrapolation of the results to the overall building stock (IEA 2002a).

The factors reported in the paper as average values for the European region (ground floor area is taken as a base (=1)) are summarized in Table 18. Similar methodology with the same availability factors has been used in Eiffert (2003).

Table 18. Solar architectural rules of thumb for BIPV potential calculation in Central Western Europe

| | Roofs | Facades |
|---|---|---|
| **Ground floor area** | 1 | 1 |
| **Gross area** | 1.2 | 1.5 |
| **Architecturally suitable area** | 0.6 | 0.2 |
| **Solar architecturally suitable area** | 0.55 | 0.50 |

*Note*: the factors are applied subsequently, i.e. the factor in a certain row of the table is applied to the result of the calculation for the row above
Source: adapted from IEA (2002)

Defaix et al. (2012) calculated the roof area available for PV installations in the EU-27 through estimation of the floor area. Floor area per capita was derived from the data on the floor area per dwelling and the average number of persons in a dwelling available from public databases. The calculated floor area per capita was multiplied with population data to estimate the total residential floor area per country. Then, the ground floor area was derived from the results on the floor area and assumptions on the number of floors in low-rise (3.5 floors) and high-rise (8 floors) residential buildings. The result was multiplied by a factor of 0.4 being to estimate the solar architecturally suitable area of a roof compared to the ground floor area in order to calculate the usable roof area for BIPV (Defaix et al. 2012).

All the studies presented above calculated roof area available for solar technologies only for certain regions, countries or cities. The only study found, which presented a methodology for available roof calculation for the whole world was Hoogwijk (2004). In the core of its methodology is the assumption that available roof area is related to income (e.g. GDP per capita), as an increase in economic welfare results in an increase in settlements, size of settlements and utilities (see Figure 20). However, the study indicates that there no correlation between the results presented in IEA (2002) and GDP per capita data from World Bank was revealed during the analysis.

Due to lack of better assumptions the author followed the logic that the less developed regions have lower GDP per capita and lower roof-top areas and created an imaginary country, representing the least developed nation, with extremely low GDP per capita and low roof-top area (100$/cap and 1 $m^2$/ cap available roof-top area). The author fitted the data from IEA (2002), using a power-law function and this imaginary point, which allowed for achieving better correlation results. This power-law fit applied to the data of the IEA was used to estimate the regional average roof-top area. Hoogwijk acknowledged that results for some regions (like Japan) were distorted, which also influenced the results of estimation for the decentralized PV potential.

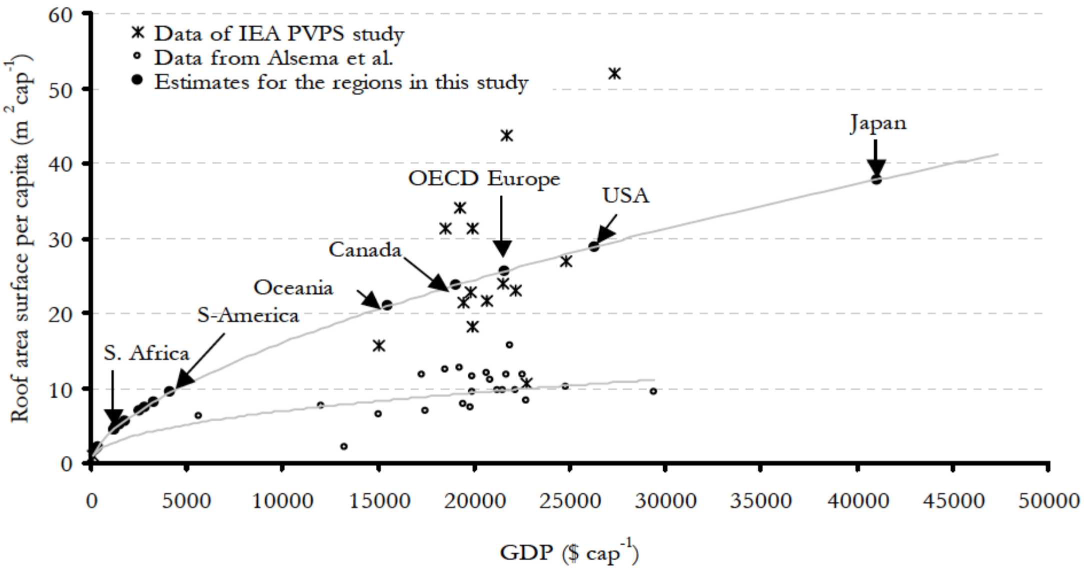



Figure 20. Roof-top area per capita suitable for decentralised PV systems plotted against the GDP per capita for the year 1995, power law fits to these data and the estimated regional GDP per capita

Source: Hoogwijk (2004)

### VI.1.3 Approach for estimating roof area available for solar installations used in BISE model

Above two approaches for estimating roof area available for solar installations have been outlined based on the analysed literature.

It has been noted that each approach has its own limitations. Geospatial approach usually requires quite detailed geospatial data with high resolution. If such data obtained and processed correctly the results of the analysis can be very robust and accurate. However, such data are very limited for many countries and often non-existent in developing regions.

Moreover, geospatial analysis involves substantial resources, such as time (if a detailed analysis is performed on a large geographic area it may require a large computation time) and human (geospatial analysis, especially with cartographic data and image processing requires advanced computer skills with specific software applications, which may not be easily obtained). The literature shows that detailed geospatial analysis is usually applied to relatively small geographical areas (a city, municipality or even a district). If larger areas are involved in the analysis the sampling is usually applied in order to extrapolate the results to a bigger region. However, sapling can be used for relatively homogeneous territories. When several diverse areas are under analysis, they have to be divided into homogeneous parts and a sampling technique should be applied for each of them with a subsequent aggregation of the results for the whole region. Therefore, the implementation of such a method on the global scale would be quite problematic, as numerous samples would have to be taken.

The relational approach seems to be more applicable for the global analysis. However, as the literature shows, the proxy for the available roof area estimation is not always straightforward, especially in case when many regions are considered. Moreover, for the analysis on the global scale the availability of data can become a problem, depending on what kind of influencing factors are considered in the estimation.

In this dissertation a combination of two approaches has been used with the aim to overcome their major limitations.

Relational part of the approach is based on the assumption that building floor area can be used as a proxy for roof area estimation. If building floor area, building height and a number of floors is known, then the roof area can be determined analytically. However, this kind of data is very region-(or even city-)specific and its availability is usually very limited. Therefore, the decision has been made to estimate roof-to-floor ratios, which can be multiplied by the floor area in order to obtain the roof area. This approach is also very useful as it allows for structuring the results of BISE model in the same way as the ones of 3CSEP-HEB model, which facilitates the comparison of the energy use estimation for different end-uses and potential solar energy production in buildings.

Floor area data have been obtained from 3CSEP-HEB model for each of the analysed region, climate zone and building type for each year between 2005 and 2050.

Roof-to-floor area values have been calculated for each region and (urban) building type within the geospatial part of the chosen approach. They have been calculated by processing the datasets for urban building areas described in Jackson et al. (2010) by means of ArcGIS software. The access to the original GIS datasets has been obtained through the communication with the authors and the four datasets were downloaded from the provided directory (Feddema 2011). Each dataset contained the location of different types of built-up areas (low, medium and high) within urban territories. Table 19 provides brief description of each urban area type, according to Jackson et al. (2010). Figure 21 and Figure 22 illustrate visualized data from the provided datasets. Also the authors provided a generic Excel dataset, which presents a number of urban areas' characteristics, including percentage of roof area for each type of built-up densities.

Table 19. Description of urban area types with different building density

| Area type | Description |
|---|---|
| **TBD** | Area of at least 1 km2 with buildings greater than or equal to ten stories tall, with a small fraction of vegetation (i.e., 5–15 % of plan area). |
| **HD** | Encompass commercial, residential, or industrial areas and are characterized by buildings three to ten stories tall with a vegetated or pervious fraction typically in the range of 5 to 25%. |
| **MD** | Area is usually characterized by row houses or apartment complexes one to three stories tall with a vegetated or pervious fraction of 20 to 60%. |
| **LD** | Areas with one- to two-story buildings and a vegetated or pervious fraction of 50 to 85%. |

Source: Jackson et al. (2010)

The key assumption, which has been made during the work with the datasheets is related to establishing the correspondence between types of built-up areas in the datasheets and the building types in the BISE model. It was assumed that single-family buildings are located in low density (LD) building areas, multi-family buildings in medium density (MD) and high density (HD) areas, while commercial and public buildings in MD, HD and tall building districts (TBD), depending on the C&P type (e.g. offices were assumed to belong to TBD). Although during personal communication the authors noted that the urban areas types do not directly correspond to a certain building type, this assumption had to be made due to the lack of a better approach (Feddema 2011). Moreover, in this dissertation the urban area types are used exclusively for roof-to-floor area ratios estimations, which are further calibrated with the building heights provided in the generic dataset.

From the geospatial data obtained the total urban built-up area has been calculated for each region and urban area type by means of the zonal statistics of the ArcGIS software. Then, the roof areas have been calculated using the data on percentages for each urban area type available from the provided file, assuming that they are the same for all climate zones within one region.

After that roof-to-floor ratio have been calculated for each region by dividing obtained urban roof area by a floor area of respective region, climate zone and building type (see Table 34).

As the datasets created by Jackson et al. include data only for urban areas the same roof-to-floor ratios are assumed for corresponding building types in rural area. Calculated roof-to-floor ratios are assumed to be constant over the analyzed time period.

Roof-to-floor ratios are subsequently multiplied by floor area (taken from 3CSEP-HEB model) of the respective regions, climate zones and building types. In the result total roof area for each region, climate zone and building type is calculated. This total roof area is further reduced through application of availability factors (see Table 35, ANNEX B. ADDITIONAL DATA ON ROOF AREA). It is assumed that solar technologies can be installed on the whole available roof area. Aperture area factor (assumed to be constant and equal to 0.9) is applied in order to estimate the actual surface of the solar system, which can receive solar radiation (Natural Resources Canada 2014).

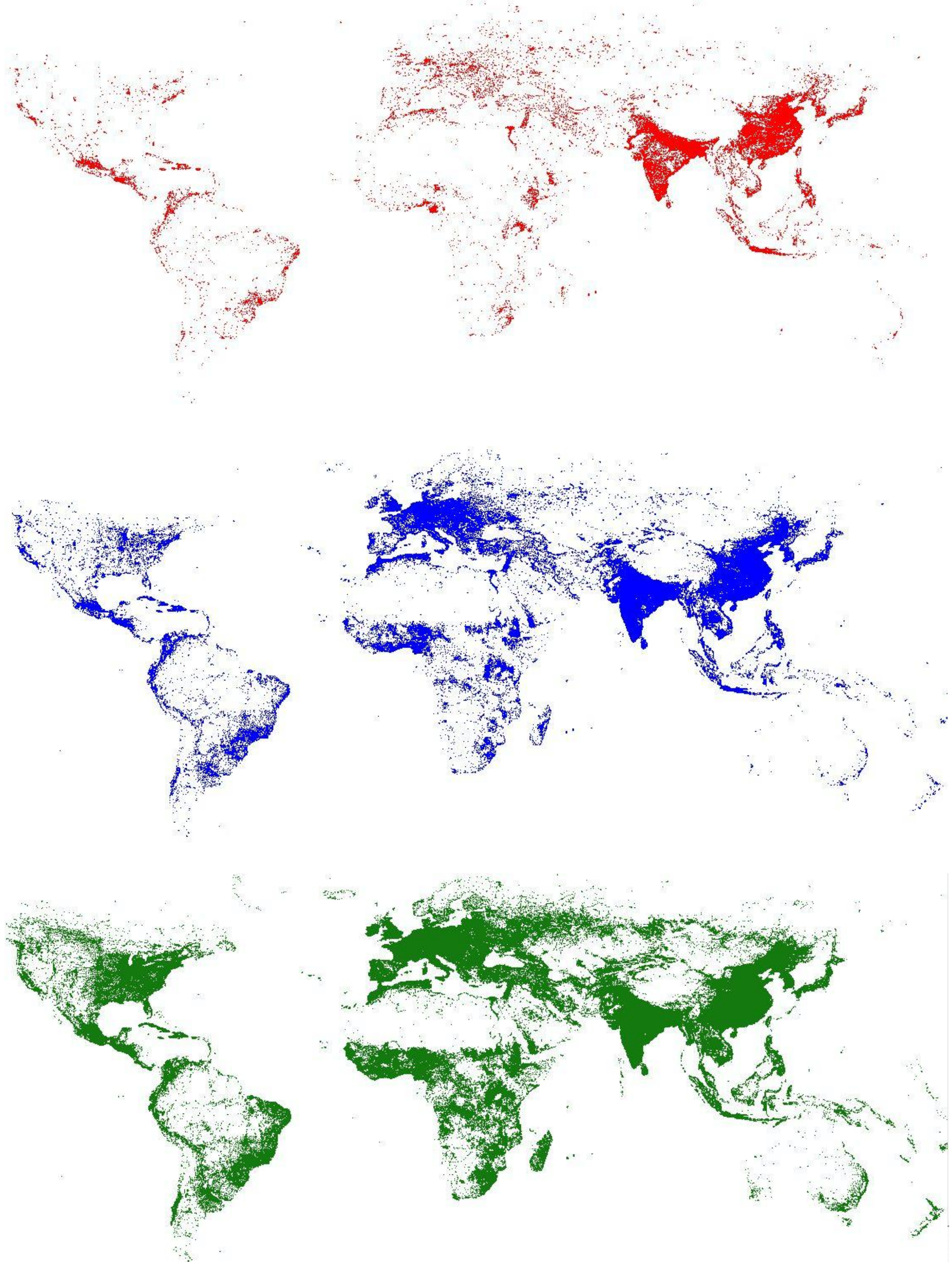
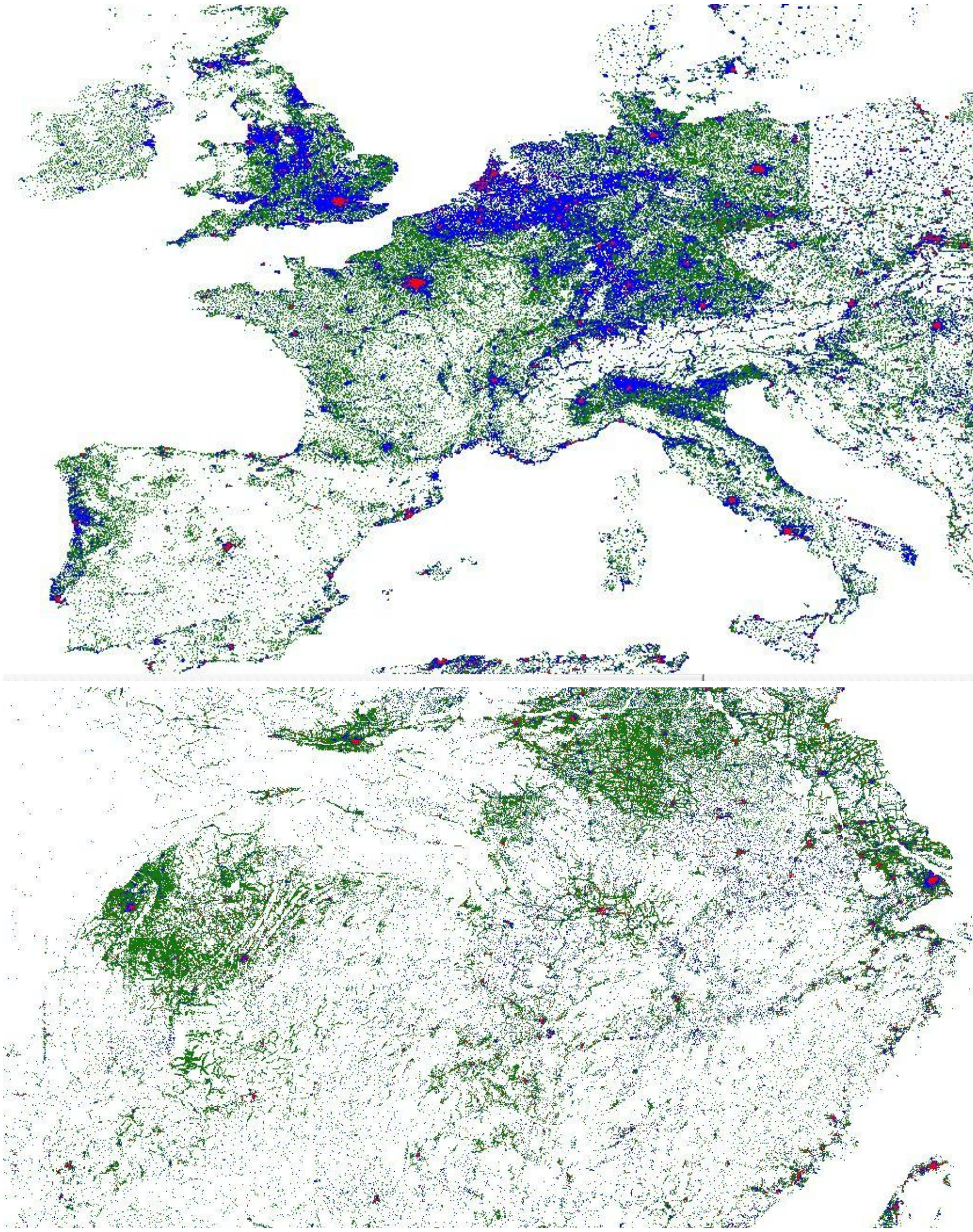


Figure 21. Illustration of different urban built-up area types, from top to bottom: HD, MD, LD[28]

[28] Illustration of the tall building districts is not provided, as they are invisible on the global map due to small area



a)

b)

Figure 22. Zoom-in view to different urban built-up area types in a) Europe and b) China

## VI.2 Results for total floor and roof areas

This section presents selected results for floor area and roof area estimations from BISE model. Visualized estimations for floor and roof areas presented in Figure 23 give the understanding of the relation between floor and roof areas in different regions and building types.

This figure presents results for two residential (single-family and multifamily buildings) and two commercial (office and educational buildings) building types in the nine selected regions. It can be seen that across the regions single-family buildings have the largest roof area in relation to the floor area, while multifamily and office buildings – the smallest. The main reason for that is difference in the building geometry: multifamily and office buildings are typically multistorey high-rise buildings, in which roof area in relation to the respective floor area is rather small. On the contrary, single-family buildings are usually one- or two-storey and have much smaller floor areas than the other two above-mentioned building types. The relation between roof and floor areas for educational buildings is somewhere between those for low- and high-rise building types and vary from region to region: for example, in NAM and CPA roof area for this building type is rather low in relation to the floor area, while in SAS and PAS it is notably higher.

General trend which can be captured from Figure 23 is that developing regions usually have larger roof areas in relation to floor area across all analyzed building types. A logical explanation for this would be that developed regions have higher number of high-rise buildings and skyscrapers, while developing regions still have large rural areas, where buildings are mostly low-rise. Even in urban centers buildings in many developing countries might be significantly lower (with certain exceptions, of course) than in developed ones.

In case of single-family buildings this difference might also be an indication for urbanization trends and housing preferences. For example, large roof in relation to floor areas in such regions, as SAS and PAS is likely to mean that single-family building are small, probably, one-storey, mostly located in rural areas and are occupied by rather low-income households. On the contrary, lower roof-to-floor ratios in NAM and WEU regions are likely to indicate that typical single-family buildings in these regions are two-storey or higher, are likely to be located in suburban areas (as the urbanization rate in these regions is quite high), which can be afforded by at least upper-middle class households.

Decrease in floor and roof area of single-family buildings and simultaneous growth of those for multifamily buildings, in, for example, CPA indicate the process of moving of the population into the cities.

The charts in Figure 23 also illustrate the population and economic growth in developing countries, which are driving the growth in residential and commercial floor and roof areas. This also means that the energy needs in these regions will grow and, therefore, low-carbon sources of energy and energy efficiency measures should become an integral part of this development in order to avoid, or at least mitigate, harmful effects of growing energy use and related greenhouse gas emissions from the building sector.

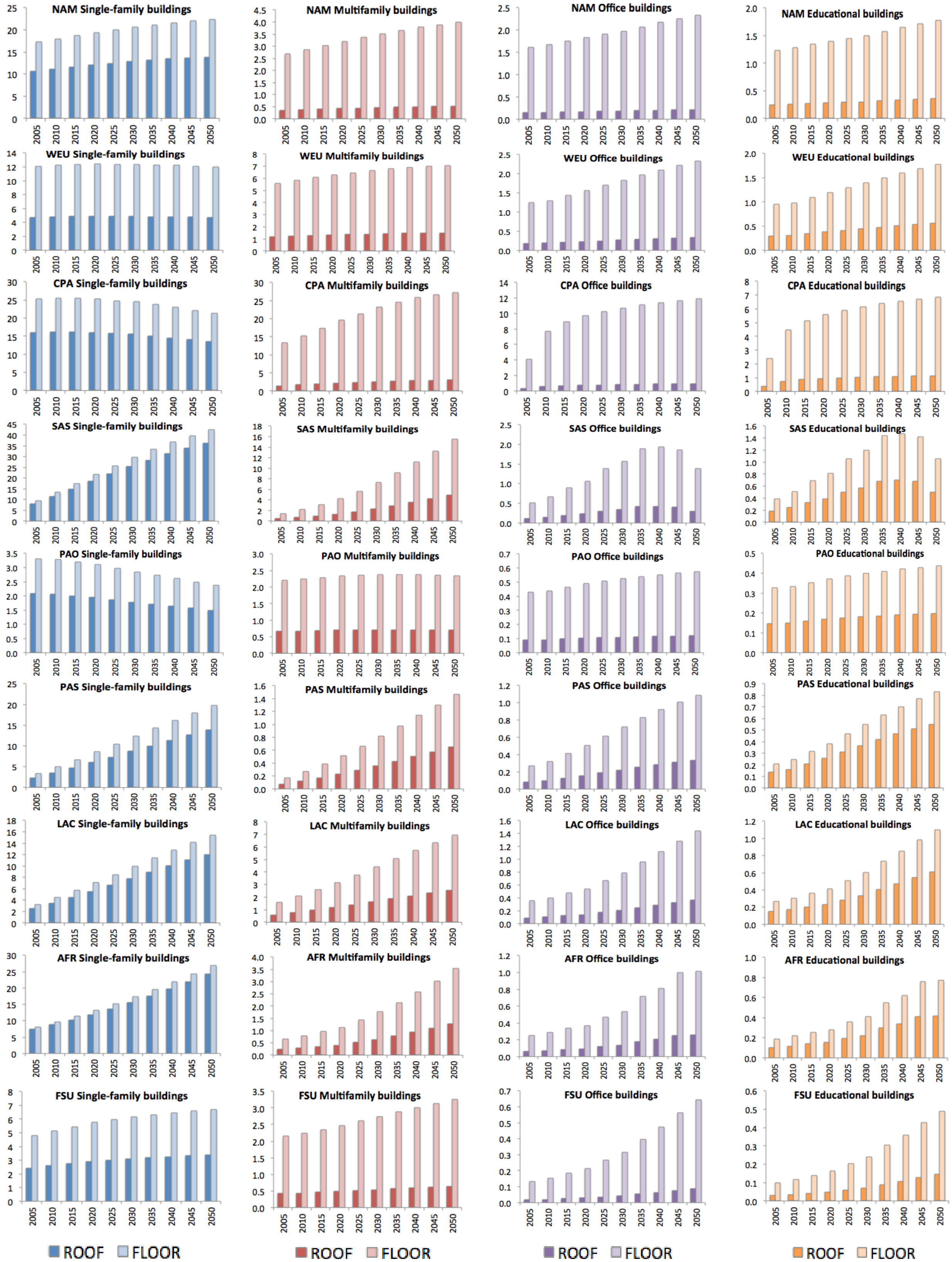



Figure 23. Roof and floor areas between 2005 and 2050 for four building types in the selected regions, bln.$m^2$

## VI.3 Results for solar system area

As it is described in Section VI.1.3, solar system area is estimated through applying certain availability factors (to account for roof facilities and shading) and aperture factor (to exclude the areas of the solar system's surfaces, which do not produce solar energy, e.g. frames, as well as the gaps between the modules) to the total roof areas.

Figure 24 presents the results of BISE model for total roof area and solar system area. For all the regions presented in the figure solar system area is about one-third of the total roof area. BISE model assumes that the whole roof area (technically) available for the solar systems installation is being utilized for solar energy production in buildings.

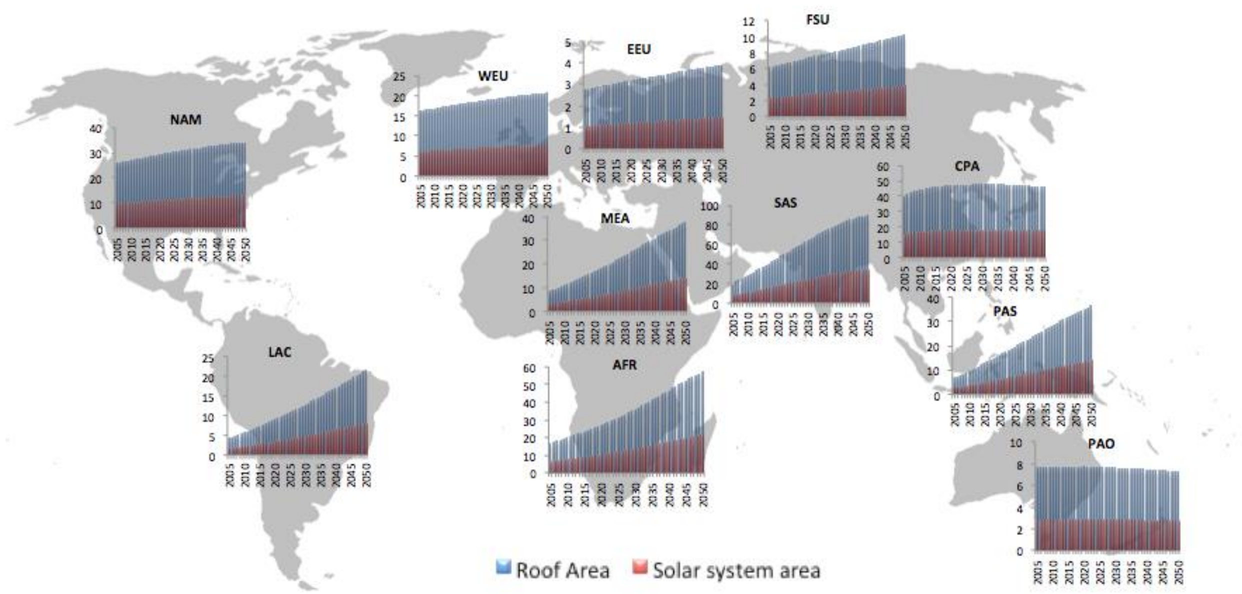



Figure 24. Results for the total roof area and solar system area in bln.$m^2$ by region

As the solar system area and the roof area available for solar system (i.e. solar system area without taking into account aperture factor) are the core parameters in BISE model, it is considered important to evaluate whether the results of BISE's estimations are in line with other studies. For this purpose an extensive data collection effort was made, which resulted in gathering and systemizing estimations of roof area available for solar technologies for more than 20 regions and countries from more than a dozen sources. A quantitative cross-regional comparative analysis was further performed with the gathered data and its results are presented in Figure 25.

The data on available roof area obtained from various sources had different metrics, scope and geographical coverage. As most studies presented estimates for residential buildings, the comparative analysis focuses on this segment of the building sector. In order for the data to be comparable across regions and studies the estimates were presented on per capita basis. Moreover, a number of sources originally used this parameter for data presentation. Most of analyzed studies report data on the country-level and mainly for European or North American countries. A few studies considered other regions, like Oceania, South America, Taiwan, Australia and Japan. In case BISE model did not have the results for certain countries (i.e. those beyond EU-27, US, China and India), the results on the roof area per capita obtained for these countries from the sources were compared to those for the most relevant BISE region, which covers those countries. Figure 25 groups results obtained for the same or similar country/region together. The results for Australia and Japan from two different sources are compared to the BISE model's estimations for PAO region. For the same reason Oceania, Taiwan and PAS region or Canada and NAM are grouped together.

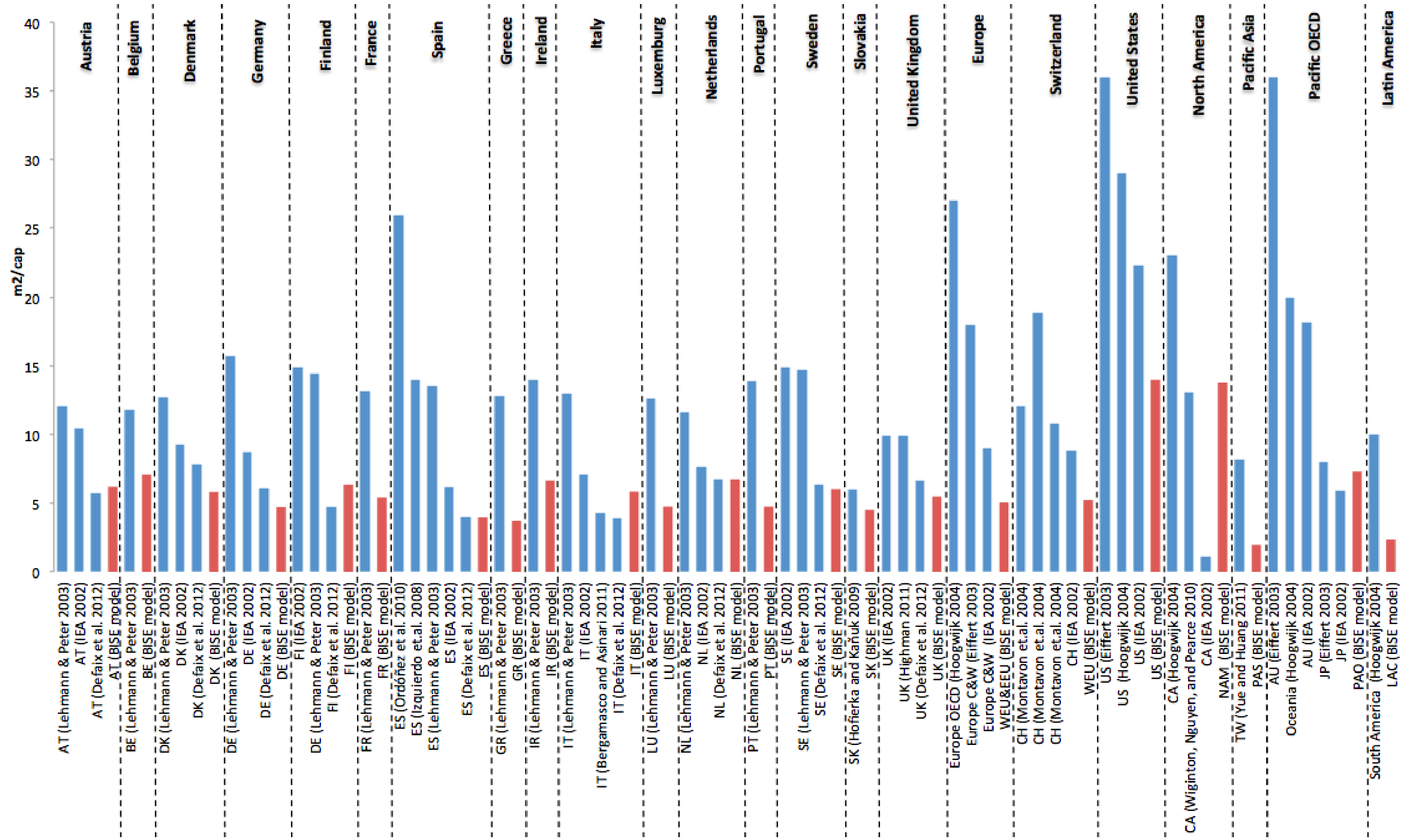





Figure 25. Results of BISE model on residential roof area per capita available for solar system installations for a number of countries/regions in comparison to the estimates obtained from different sources. The data behind the figure can be found in Table 36 (Annex B)

*Note*: difference in the presented results can be explained by different methodologies, assumptions and input data used in different studies

Figure 25 demonstrates a very high level of dispersion in the results from different sources within each geographical group. For example, estimations for Australia from one source is almost two times higher than from the other. Estimation of BISE model for PAO region, which besides Australia includes Japan and New Zealand, is more in line with the result for Japan presented from other sources.

As a general trend, which can be observed in the figure, is that BISE estimates typically have the same order of magnitude as other studies. In absolute terms for a number of regions (e.g. Austria, Spain, Italy, the Netherlands, Sweden, Canada/NAM, Japan) BISE's results are very similar to some studies presented for the same region. For other regions, however, this difference is more evident (e.g. France, Greece, Ireland, Luxemburg, WEU/EEU, US).

There are many factors that can explain these variations in the results. For example, difference in methodologies, assumptions and input data. BISE results might be lower as this model takes into account both shading and roof facility factors, while many studies apply different types of factors, with less significant roof area reductions. Moreover, BISE model considers high-rise multifamily buildings within residential category, while in a number of sources it is not clear what types of residential buildings are analyzed. BISE roof-to-floor factors may present another source of uncertainty, as these parameters are approximated for large geographical areas based on the data from different sources. Another possible factor is that very often the data are presented for different years: the analyzed sources are dated between 2002 and 2012, which makes comparison more difficult. The main conclusion from the comparative analysis is that BISE model presents rather conservative estimations of the roof area, which in combination with assessment of the technical potential for state-of-the-art solar energy technology is expected not to distort results significantly.

# VII CHAPTER. SOLAR ENERGY AND ENERGY USE MODELING

Estimation of the solar energy potential is the crucial part of this dissertation and the main purpose of BISE model. As any other model BISE model presumes the application of a number of assumption in order to enable the calculation of the results at the large scales. The aim of this chapter is to present the key assumptions for calculation of the solar potential both for solar thermal and solar electric energy and explain the process of adaptation and modification of the data from 3CSEP-HEB and BUENAS models, which were necessary for enabling their results utilization in BISE model..

## VII.1 Assumptions for solar energy supply modelling

As has been noted above, the BISE model provides the results for the potential thermal and electric solar energy production of hybrid PV/T technologies at the regional or global level and not for the individual solar system. In order to find the compromise between the model's robustness, on the one hand, and reasonable calculation time and data availability, on the other, certain simplifications and assumptions had to be introduced.

This section presents the key assumptions for the crucial model's parameters, following the logic of their appearance in Sections V.2.2 - V.2.3. The justification for the assumption on the worldwide applicability of the PV/T technologies is also given in Section VII.1.4.

### VII.1.1 Assumptions for calculating hourly total solar radiation on the plane of the solar system's array

The parameters needed for calculation of the hourly irradiation on the plane of the solar system's array, which are not the results of the intermediate calculation steps, are derived from the Section V.2.2, Step 7 and presented in Table 20. For the easier reference the formula for calculating this parameter is presented here as well:

$$I_T = I_B R_b + I_D \left(\frac{1 + \cos\beta}{2}\right) + I_{glob}\, \rho \left(\frac{1 - \cos\beta}{2}\right)$$

Table 20. Parameters for calculation of the hourly irradiation on the plane of the solar system's array

| Parameter | Symbol | Calculation step | Assumption is made (YES/NO) |
|---|---|---|---|
| **Hourly global solar irradiation per $m^2$** | $I_{glob}$ | 4 | NO – input data |
| **Hourly top-of-atmosphere solar radiation per $m^2$** | $I_{TOA}$ | 4 | NO – input data |
| **Hourly beam solar irradiation per $m^2$** | $I_B$ | 6 | NO – calculated |
| **Hourly diffuse solar irradiation per $m^2$** | $I_D$ | 5 | NO – calculated |
| **Tilt angle of the solar system** | $\beta$ | 7 | YES – see Table 21 |
| **The ratio of beam radiation on the solar array to that on the horizontal surface** | $R_b$ | 7 | YES – see Table 22 |
| **The portion of the global solar radiation reflected from the ground** | $\rho$ | 7 | NO – input data |

Table 20 shows that for two parameters involved in the calculation of the hourly irradiation on the plane of the solar system's array, - namely the tilt angle of the solar system's array and the ratio of beam radiation on the solar array to that on the horizontal surface, - the assumptions have been made.

In order to maximize the production of the solar energy by building-integrated technologies, the solar system's surface should be oriented directly towards the equator (facing south in the northern hemisphere and north in the southern one) and mounted with the optimal tilt angle. The optimum tilt angle of the system is usually calculated with the latitude of the location and the angle variations of 10–15 ◦C, depending on the application (Tyagi et.al. 2012).

In this study the optimal tilt angle is assumed for the PV/T solar systems in all[29] regions and building types, being calculated, according to the rules applicable for solar panels, presented in Table 21. The performance of the solar systems can be further improved through the seasonal adjustment of the system's tilt angles (Mahdi et al. 2011). However, in this study no assumptions for the seasonal adjustments are made, as these adjustment are not yet used on the large scale.

Table 21. Estimation of the optimal tilt angle of the solar system

| Latitude (φ) | Tilt angle |
|---|---|
| 0 – 15 | = 15 |
| 15 – 25 | = φ |
| 25 – 30 | = φ + 5 |
| 30 – 35 | = φ +10 |
| 35 - 40 | = φ + 15 |
| 40 + | = φ + 20 |

Source: OkSolar (2012)

The data for the ratio of beam radiation on the solar array to that on the horizontal surface ($R_b$) are given in Table 22.

Table 22. $R_b$ values as function of the latitude ($\varphi$) and the difference between the latitude and the tilt angle ($\varphi$ $\beta$), for $\varphi$ $\beta$ $30^\circ$

| φ | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 0.59 | 0.69 | 0.83 | 1.00 | 1.13 | 1.20 | 1.17 | 1.05 | 0.90 | 0.74 | 0.61 | 0.56 |
| **5** | 0.62 | 0.72 | 0.84 | 0.98 | 1.09 | 1.14 | 1.12 | 1.03 | 0.90 | 0.76 | 0.65 | 0.59 |
| **10** | 0.67 | 0.75 | 0.86 | 0.97 | 1.06 | 1.10 | 1.08 | 1.01 | 0.90 | 0.79 | 0.69 | 0.64 |
| **15** | 0.72 | 0.79 | 0.88 | 0.97 | 1.03 | 1.06 | 1.05 | 0.99 | 0.91 | 0.82 | 0.74 | 0.70 |
| **20** | 0.79 | 0.85 | 0.91 | 0.97 | 1.02 | 1.04 | 1.03 | 0.99 | 0.93 | 0.87 | 0.80 | 0.77 |
| **25** | 0.88 | 0.91 | 0.95 | 0.98 | 1.01 | 1.02 | 1.01 | 0.99 | 0.96 | 0.93 | 0.89 | 0.87 |
| **30** | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| **35** | 1.16 | 1.11 | 1.07 | 1.03 | 1.00 | 0.99 | 0.99 | 1.02 | 1.05 | 1.10 | 1.15 | 1.18 |
| **40** | 1.39 | 1.26 | 1.15 | 1.06 | 1.01 | 0.98 | 0.99 | 1.04 | 1.11 | 1.22 | 1.35 | 1.43 |
| **45** | 1.72 | 1.46 | 1.26 | 1.11 | 1.02 | 0.99 | 1.00 | 1.07 | 1.19 | 1.39 | 1.64 | 1.81 |
| **50** | 2.24 | 1.75 | 1.41 | 1.17 | 1.04 | 0.99 | 1.01 | 1.11 | 1.30 | 1.62 | 2.08 | 2.44 |
| **55** | 3.16 | 2.19 | 1.60 | 1.25 | 1.06 | 1.00 | 1.03 | 1.16 | 1.44 | 1.95 | 2.83 | 3.63 |
| **60** | 5.17 | 2.91 | 1.88 | 1.34 | 1.09 | 1.00 | 1.04 | 1.22 | 1.62 | 2.47 | 4.30 | 6.64 |
| **φ** | **Jul** | **Aug** | **Sep** | **Oct** | **Nov** | **Dec** | **Jan** | **Feb** | **Mar** | **Apr** | **May** | **Jun** |

*Note*: For the latitude equal or great than zero (Northern Hemisphere) months on the top should be used, for latitudes less than zero (Southern Hemisphere) – at the bottom. The absolute value of the latitude should be used

[29] Such an assumption is very ambitious and in practice cannot be followed all the time, therefore, certain reducing factors for certain building vintages (e.g. retrofit buildings) were introduced and will be noted below

The data for this parameter have been borrowed from Appendix D of Duffie and Beckman (1991) and for every five degrees of the latitude and for various values of the difference between the latitude and the tilt angle from +30 to -30 degrees with the step of 5 degrees and vary depending on the difference between the latitude and the tilt angle equal to +30 degrees are given. The data presented in the source are calculated by the authors as a function of the latitude and the difference between the latitude and the tilt angle.

### VII.1.2 Assumptions for calculating solar electric energy supply

The main formulas for calculating solar electric energy supply are provided in Section V.2.3, Steps 8 - 11 and are repeated here for the reference purposes:

$$\eta_{elec} = \eta_r \times (1 - \beta_p \times (T_c - T_r))$$

$$T_c - T_{amb} = (219 + 832K) \times \frac{NOCT - 20}{800}$$

$$E_{El\ output} = I_T \times \eta_{elec}$$

$$E_{El\ prod} = E_{El\ output} \times (1 - L_{miscel})$$

$$E_{El\ supp} = E_{El\ prod} \times \eta_{inverter}$$

The parameters needed for calculation of the electric solar energy supply, which are not the results of the intermediate calculation steps, are presented in Table 23.

Table 23. Parameters for calculation of the electric solar energy supply

| Parameter | Symbol | Calculation step | Assumed value | Reference |
|---|---|---|---|---|
| **Reference temperature** | $T_r$ | 8 | 25°C | RETScreen (2004a) |
| **Temperature coefficient** | $\beta_p$ | 8 | 0.4 %/°C | RETScreen (2004a) |
| **Reference efficiency** | $\eta_r$ | 8 | 13% | RETScreen (2004a) |
| **Nominal Operating Cell Temperature** | NOCT | 8 | 45°C | RETScreen (2004a) |
| **Miscellaneous losses** | $L_{miscel}$ | 10 | 1% | SolarCity Partnership (2012) |
| **Inverter efficiency (taking into account wiring losses)** | $\eta_{inver}$ | 11 | 90% | Vardimon (2011) |

For all parameters presented in Table 23 certain assumptions have been made. As there is a vast number of PV module configurations is available on the market and can be integrated into PV/T technology the assumption on the type of the PV module had to be made. In this study the parameters' values for a typical Mono-Si PV module are used. Mono-Si PV module has been chosen as one of the most cost-effective solutions widely available on the market (see Section III.2.1). Although the efficiency of the PV modules is increasing due to developments in the PV design and characteristics, a conservative assumption on the fixed reference efficiency ($\eta_r$) of the technology has been made due to high uncertainty of future technological progress in the field.

### VII.1.3 Assumptions for calculating solar thermal energy supply

The main formulas for calculating solar thermal energy supply are provided in Section V.2.4, Steps 13 - 18 and are presented here for the reader's reference:

$$U_L = \left\{\frac{N \times T_{pl}}{C \times \left[\frac{(T_{pl} - T_a)}{(N - f)}\right]^e} + \frac{1}{h_w}\right\}^{-1} + \frac{\sigma \times (T_{pl} + T_a) \times (T_{pl}^2 + T_a^2)}{(\varepsilon_p + 0.00591\, h_w)^{-1} + \frac{[2N + f + 0.133\varepsilon_p]}{\varepsilon_g} - N}$$

$$F_R = \frac{\dot{m}\, c_p}{A_S\, U_L} \times \left(1 - e^{-F' A_S U_L / \dot{m} c_p}\right)$$

$$E_{TH\ output} = F_R \times (I_T \times (\tau\alpha - \tau \times \eta_{elec}) - U_L \times (T_{in} - T_a))$$

$$T_{out} = T_{in} + \frac{1}{M\, c_p} \times E_{TH\ output}$$

$$T_S = T_{in} + \frac{1}{M\, c_p}\, E_{TH\ output} \times L_{TH}$$

$$T_{pl} = T_{in} + \frac{E_{TH\ output}}{2\dot{m}\, c_p} + \frac{E_{TH\ output}}{A_s\, h_{ca}}$$

$$E_{TH\ supp} = E_{TH\ output} \times (1 - L_{TH})$$

The parameters needed for calculation of the thermal solar energy supply, which are not the results of the intermediate calculation steps, are presented in Table 24.

Table 24. Parameters for calculation of the thermal solar energy supply

| Parameter | Symbol | Calculation step | Assumed value | Reference |
|---|---|---|---|---|
| **Ambient air temperature** | $T_a$ | 13 | NO – input data | |
| **Wind speed** | $V_w$ | 13 | NO – input data[30] | |
| **Stefan–Boltzmann constant** | $\sigma$ | 13 | $5.670373(21)*10^{-8}$ $[Wm^2K^{-4}]$ | Kakham et al. (2012) |
| **Absorber plate emissivity** | $\varepsilon_p$ | 13 | 0.93[29] | Tripanagnostopoulos et.al (2000) |
| **Glass emissivity** | $\varepsilon_g$ | 13 | 0.9 | Reynolds et al. (2004) |
| **Efficiency factor** | $F'$ | 14 | 0.92[31] | Góngora-Gallardo et al. (2013) |
| **Flow rate** | $\dot{m}$ | 14 | 0.026[28] [kg/s] | Góngora-Gallardo et al. (2013) |
| **Specific heat capacity** | $c_p$ | 14 | 4186 [J/kg/°C] | RETScreen (2004b) |
| **Transmittance of the cover** | $\tau$ | 15 | 0.9 | Matuska et.al (2009), Pluta (2011) |
| **Absorptivity of the absorber** | $\alpha$ | 15 | 0.94[32] | Tripanagnostopoulos et.al (2000) |
| **Mass of the water in the storage tank[33]** | $M$ | 16 | 100 [kg] | Author's assumption |
| **Inlet fluid temperature for the first hour of sunlight** | $T_{in}$ | 16 | 18°C | (Tripanagnostopoulos 2013) |
| **Mean plate temperature for the first hour of sunlight** | $T_{pl}$ | 17 | $T_{in}$ + 10°C | Dadioti (2010) |
| **Heat transfer coefficient between the solar cells and the copper absorber** | $h_{ca}$ | 17 | 20% | Sok et.al (2010) |
| **Thermal system's losses** | $L_{TH}$ | 18 | 20% | Sok et.al (2010) |

Not the whole amount of solar radiation received on the surface of the solar system can be used for energy generation: one part of this radiation is reflected back to the sky, another component is absorbed by the glazing and the remaining part is transmitted through the glazing to the absorber plate. Therefore, the transmittance of the cover ($\tau$) stands for the percentage of the solar radiation transmitted through the cover, emissivity for the relative ability of the surface to emit energy by radiation ($\varepsilon$) and absorptivity of the absorber ($\alpha$) represents the percentage being

[30] Wind speed is not input data itself, however, it is computed directly from the input data on two wind components (see calculation Step 13, Section V.2.4)
[31] The most frequent value is taken from Table 2, Góngora-Gallardo et al. (2013)
[32] Value for a black absorber was assumed
[33] As all the calculations till the very last step are accomplished per one square meter of the solar system area, it is assumed that one square meter of the solar system area requires 100 kg of water in the storage tank

absorbed. The absorbption of the heat from the solar radiation by the system causes the increase of the system's temperature higher than the one of the surroundings. This temperature difference leads to the heat loss through the convection and radiation. The amount of the heat lost during these process is largely determined by the overall heat transfer coefficient ($U_L$) (Struckmann 2008).

This study does not aim at testing the performance of a concrete individual solar system and rather investigates the potential of a "generic" technology with typical characteristics, presenting the results in the aggregated way on the regional and global scales. Therefore, the assumption that certain parameters related to the physical characteristics of the thermal part of the solar system are constant has been made (see Table 24).

The inlet fluid temperature (the temperature required in the storage tank) for the first hour of the sunlight has been assumed constant and the same across the regions, due to unavailability of such detailed measured data at the regional scale. Moreover, it is technically possible to maintain the inlet fluid temperature at approximately the same level (e.g. during the night) using the cross flow heat exchanger and the constant temperature circulator (Abdullah et.al 2003).

The thermal losses account for the share of the heat lost through the pipes, storage tank and heat exchanger and assumed at the level of 20% of the collected solar radiation (Sok et.al 2010).

### VII.1.4Assumption on PV/T applicability in different conditions

The key assumption of the BISE model is that hybrid building-integrated PV/T technologies can potentially be applicable worldwide. This study does not evaluate how probable this assumption can be, but rather aims at illustrating the technical potential of this state-of-the-art technology on the global and regional scales.

A logical question may be posed in respect to such an ambitious assumption: whether it is technically feasible to use PV/T technologies under different climatic conditions, including extremely cold and hot climates.

According to Hasan and Sumathy (2010), PV/T technologies are applicable in buildings located in very different climates, both cold and warm. In the former ones produced thermal energy can be used for space heating, while in the latter ones – for space cooling. The review also indicates that "with an optimal design, PV/T systems can supply buildings with 100% renewable electricity and heat in a more cost-effective manner than separate PV and solar thermal systems" (Hasan and Sumathy 2010).

The solar systems are assumed to have no decline in the performance over its lifetime and no salvage value.

## VII.2 Assumptions for space heating, space cooling and water heating energy use modelling

As it has been described in Section V.1.1, the data on the energy use for space heating, space cooling and water heating were borrowed from the 3CSEP-HEB model (for more details see - Urge-Vorsatz, Petrichenko, et al. 2012). In the 3CSEP-HEB model the energy use for space heating and cooling are calculated together, based on the energy intensities, which include energy needs for both of these end-uses. For the purpose of the BISE model, however, it is important to have the estimations separately for space heating and cooling, as these end-uses usually require different types of energy sources. Therefore, in the BISE model it is assumed that solar thermal energy (or solar heat) is needed for meeting energy needs for space heating and water heating, while solar electricity output from the PV part of the hybrid system can be utilized for space cooling, lighting and appliances. Moreover, in 3CSEP-HEB model all estimations of the energy use are performed on the annual basis, while for the BISE model it is important to have at least monthly results, as the variation in the potential solar energy supply among different months can be very significant. Monthly estimations are also important due to limited availability of long-term solar energy storage. BISE model does not assume transfer of the potentially produced solar energy from one month to another (but allows for the storage of unused solar energy within one month).

Therefore, the results for space heating and cooling obtained from the 3CSEP-HEB model needed further modifications and adaptation to the BISE model's needs. The key modifications of these results are: 1) separation between heating and cooling energy uses, 2) estimation of the monthly values (separately for space heating and space cooling) based on the annual results.

These two processes are performed in BISE model simultaneously based on the number of heating and cooling degree-days. BISE model incorporates an approximation algorithm for calculating heating (HDD) and cooling degree-days (CDD) based on the daily values for the ambient temperature obtained from NASA archives (see Section V.3). The algorithm estimates an average daily ambient temperature for every day of the year and for every coordinate of the input data. Then this value is subtracted from the 'base' heating temperature. If the value is less than or equal to zero, that day has zero HDD. If the value is positive, then this number represents the number of HDD on that day. Similar logic is applied for calculating CDD. However, CDD are counted in case the ambient temperature is higher than the 'base' cooling temperature, i.e. 'base' cooling temperature is subtracted from the ambient temperature: positive value indicates the number of CDD, while negative or zero value stands for zero CDD.

'Base' temperatures in BISE model are assumed separately for heating and cooling degree days calculation and are specified for each region (see Table 25). 'Base' heating temperature means the level of the ambient temperature, above which heating is not needed. 'Base' cooling temperature reflects the temperature, above which cooling is needed.

'Base' heating temperature is usually set between 14 and 22°C, while 'base' cooling temperature is typically in the range between 18 and 28°C (Büyükalaca, Bulut, and Yılmaz 2001).

In this dissertation for some regions (usually developing regions with hot climate) the 'base' cooling temperature is set at a relatively high level (24-25°C). It is done in order to reflect different thermal comfort levels in these regions: as the air-conditioning is a relatively young end-use, an outdoor temperature threshold, when people start to feel discomfort and need for space cooling, is often several degrees higher than in developed regions. Although these assumptions are still quite subjective and are based on the expert judgment (e.g. Jiang 2012), the author believes that they reflect the reality better than a simple transfer of the common base temperatures (20-21°C) from the developed countries (e.g. US).

Table 25. 'Base' temperatures for calculating Heating and Cooling Degree Days in the BISE Model

| Region | Base Heating Temperature, C | Base Cooling Temperature, C |
|---|---|---|
| **AFR** | 18 | 25 |
| **CPA** | 16 | 24 |
| **EEU** | 15 | 21 |
| **FSU** | 15 | 22 |
| **LAC** | 18 | 25 |
| **MEA** | 18 | 25 |
| **NAM** | 16 | 20 |
| **PAO** | 15 | 23 |
| **PAS** | 18 | 25 |
| **SAS** | 18 | 24 |
| **WEU** | 15 | 21 |

HDD and CDD are summed up for every month and for the whole year. Certain thresholds are applied for monthly HDD and CDD, below which no heating or no cooling are assumed. After that the annual numbers of HDD and CDD are summarized to provide a generic total value. This value is then used to calculate monthly weights separately for heating and cooling. In other words, the monthly HDD value divided by the generic total provides the weight for heating in the total energy use for space heating and cooling in each month, while the monthly CDD value divided by the generic total provides a similar monthly weight for cooling. Then, these monthly heating and monthly cooling weights are multiplied by the annual energy use value for space heating and cooling (for every region, climate zone, building type and building vintage) to acquire energy use values for every month separately for space heating and cooling.

It has to be noted that calculation of HDD and CDD uses a simplified methodology, as it is not the purpose of this dissertation to provide precise values for these parameters, but rather to elaborate a robust proxy for splitting results for space heating and cooling into two end-uses and, on the other, - to derive monthly estimates from the annual total separately for space heating and space cooling.

As for water heating, it is assumed that the variation in this type of the energy use among the months can be neglected and, therefore, annual energy use for water heating is equally spread along the months.

Figure 26 illustrates energy intensities separately for space heating, space cooling and water heating for the year 2050 and five selected regions under Deep scenario. For the purpose of comparison the results are presented for two building types: single-family and office buildings.

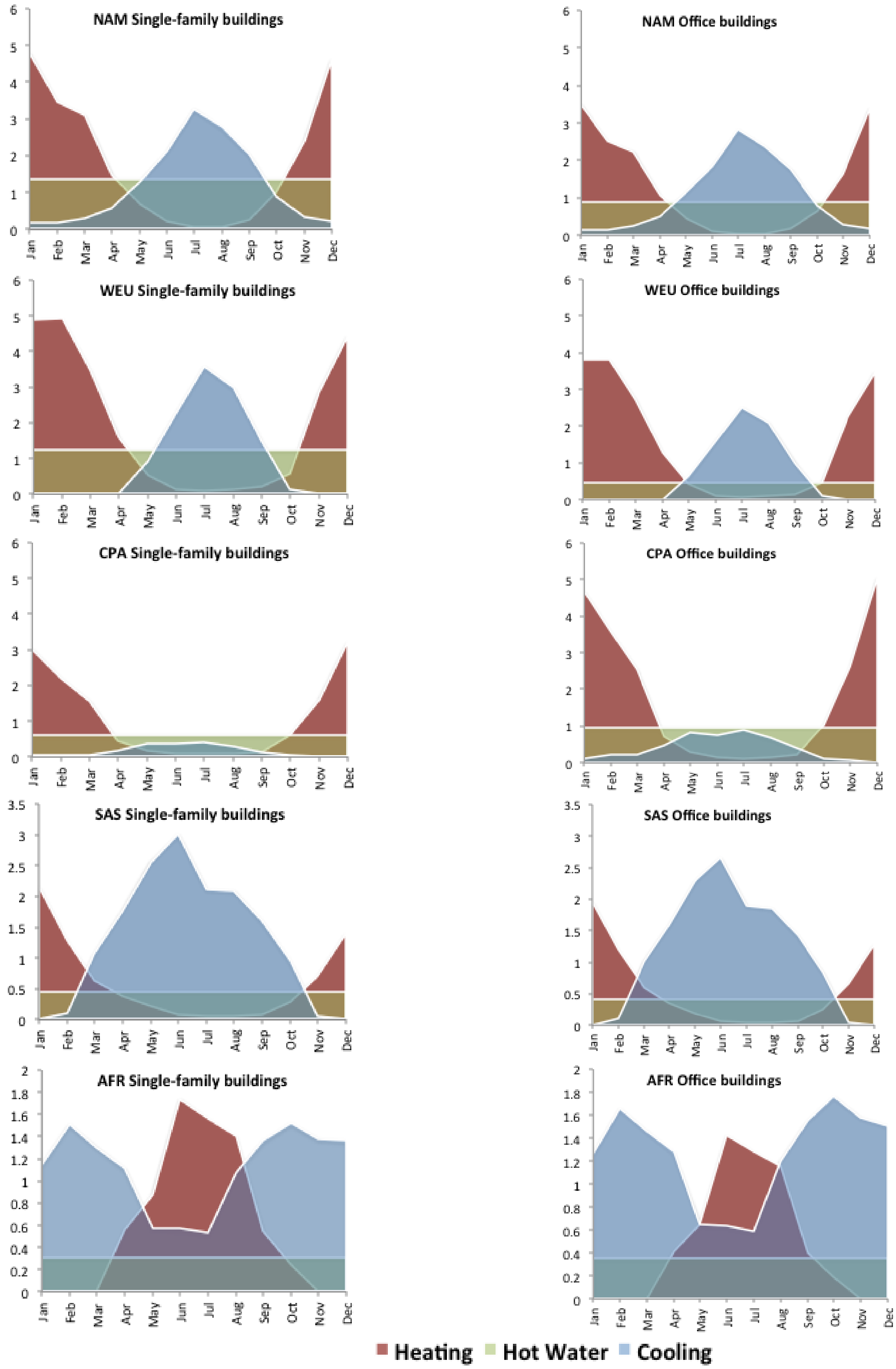



Figure 26. Monthly energy intensities (kWh/m2) for space heating, space cooling and water heating in single-family and office buildings in 2050 under Deep scenario for five selected regions

## VII.3 Assumptions for appliances and lighting energy use modelling

As it was noted in Section V.1.2, the input data for energy use for appliances and lighting used in BISE model are coming from BUENAS model. However, due to different geographical and methodological structures of BUENAS and BISE models certain modifications with appliances and lighting data had to be made prior their utilization for the purposes of this dissertation.

There are several reasons for performing modifications with BUENAS data, which are described below:

1. BUENAS model provides results for 11 countries and EU-27, while BISE model primarily deals with 11 larger regions (see ANNEX A. REGIONAL DIVISION).
2. BUENAS model estimates total energy use for appliances and lighting for the whole country, while BISE model, following the logic of the floor area calculation of 3CSEP-HEB model, is more dynamic and requires utilization of energy intensities (in kWh/m$^2$) of exemplary buildings for each climate zone, building type and vintage, which are then used to estimate the total energy use in the country or region.
3. BUENAS model provides the data aggregated into commercial and residential sectors, while BISE model has a more detailed building typology (several residential building types and commercial sub-categories).
4. BUENAS model contains data for the period between 2010 and 2030, while BISE model covers the period between 2005 and 2050.
5. BUENAS model considers different types of appliances. For BISE model, however, the aggregated appliances energy consumption in different building types is of interest.

6. Results for energy use in BUENAS model is presented on the annual basis, while for BISE model monthly values are needed.

The first point has been addressed by making certain assumptions on the connection between BUENAS countries and 11 regions in BISE model (see Table 26). The rationale behind these assumptions is to select a country from the BUENAS list, which can be considered representative for each region in BISE model in terms of the patterns in energy use for lighting and appliances. This kind of approach becomes possible because BISE model works under performance-based approach, i.e. the main input data for the energy use estimation in this model is specific energy consumption in kWh/m$^2$, which, in the situation of the lack of data, is assumed not to have significant differences between selected countries and respective larger regions. The author understands that this kind of assumption is accompanied by high level of uncertainty, however, due to the absence of better estimates for such a broad geographical coverage and taking into account that calculation of the energy use for appliances and lighting is not the primary goal of this research and is done only for comparative and illustrative purposes (to enable comparison between solar electricity and electrical energy needs), such an approximation is considered to be acceptable.

Table 26. Assumptions for the connection between countries in BUENAS and regions in BISE model

| Model | Countries/ Regions | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **BISE** | NAM | WEU, EEU | CPA | SAS | PAO | PAS | FSU | LAC, MEA | AFR |
| **BUENAS** | US | EU-27 | China | India | Japan | Indonesia | Russia | Mexico | South Africa |

In order to obtain energy use per square meter, as required for BISE model, the total energy use for each country selected from BUENAS model had to be extrapolated for the larger regions used in BISE model. It was done in a different way for residential and commercial sectors.

Residential energy use (separately for appliances and lighting) in each of selected BUENAS countries was divided by population in this country for each year of the analysis, resulting in the energy use per capita. After that the estimations for the energy use per capita were multiplied by the population in the corresponding larger region for each year, thereby providing the total energy consumption (for lighting or appliance) in the region. After that this total for each year was divided by the total residential floor area in the corresponding year. The result is the targeted energy intensity in kWh/m$^2$. Extrapolation for the commercial energy use was done in a similar manner with the difference that instead of population, GDP data was used and, therefore, energy use per USD of GDP was utilized as the key parameter for energy use estimation in the larger regions.

For such regions, as NAM, CPA, SAS, WEU and EEU, in which BUENAS countries (US, China, India, EU-27) play the dominant role and for which there are floor area estimates in 3CSEP-HEB model, the extrapolation was done in a different way. The energy intensities (i.e. energy use per square meter separately for lighting and appliances) were calculated for BUENAS countries by dividing energy use results for these countries from BUENAS model by floor area results from 3CSEP-HEB model. The obtained energy intensities were used in the larger regions, used in BISE model. In order to calculate total energy use for lighting or appliances in a certain 'large' region the acquired energy intensities were multiplied by the respective floor area for these regions obtained from 3CSEP-HEB model.

Calculated from BUENAS' data residential or commercial energy intensities for lighting and appliances within a certain region are assumed to be the same among residential or commercial building types and sub-categories due to the lack in data for such differences.

As BUENAS model contains estimation for lighting and appliances energy use only for 2010-2030, the data were approximated for the period 2005-2050 accepted in BISE model, by means of linear extrapolation and in some cases by means of different types of regression, using the functions, which fit the best the trends in the available data.

It has to be noted that although BUENAS model considers different types of residential and commercial appliances, BISE model developed for this dissertation deals with the overall energy intensities for residential and commercial appliances. Moreover, the availability of the data for different appliance types in BUENAS model differs between sectors (residential vs commercial) and among countries. In order to maintain the consistency in the set of selected appliances among the countries and, thereby, make the results for the appliances energy use comparable among the regions, the list of appliances, which is considered in BISE model had to be elaborated in a way that all selected appliance types are present in all the analyzed countries. For commercial sector appliances include mostly refrigeration, while appliances for the residential sector include refrigeration, television, fans and stand-by. The list of appliance types, for which the data are available in BUENAS model for each country can be found in Table 37 (Annex C).

A very important assumption in BISE model had to be made regarding the choice of the scenario from BUENAS model. As it is described in Section V.1.2, BUENAS model includes two scenarios: Business As Usual (BAU) and Best Practice Scenario (BP) (McNeil et al. 2012). Although for BISE model BP scenario would have been more appropriate in terms of its assumptions on the ambitious efficiency improvements, which are in line with the assumptions of 3CSEP-HEB Deep scenario on wide proliferation of the state-of-the-art best-practices for space heating, cooling and water heating. However, due to more limited data coverage in case of BP scenario (e.g. at the moment of preparation of this dissertation the results for commercial sector were not available) it was decided to use the results of BAU scenario in BISE model. In this dissertation interpretation of the results acknowledges this assumption.

Figure 27 and Figure 28 present energy intensities for lighting and appliances, respectively, calculated for each ‘big’ region and for the period of 2005-2050 from the results of BUENAS BAU scenario, based on the assumptions and methodology described above.

Annual energy use intensities have been further disaggregated in order to obtain values for each month. In case of appliances it was assumed that energy consumption for this end-use does not vary significantly from one month to another and, therefore, annual energy use was equally divided between twelve months.

Lighting energy use was spread among the months proportionally to the average number of dark hours in each month for a particular region and climate zone. Number of dark hours was calculated from the input data on hourly solar radiation.

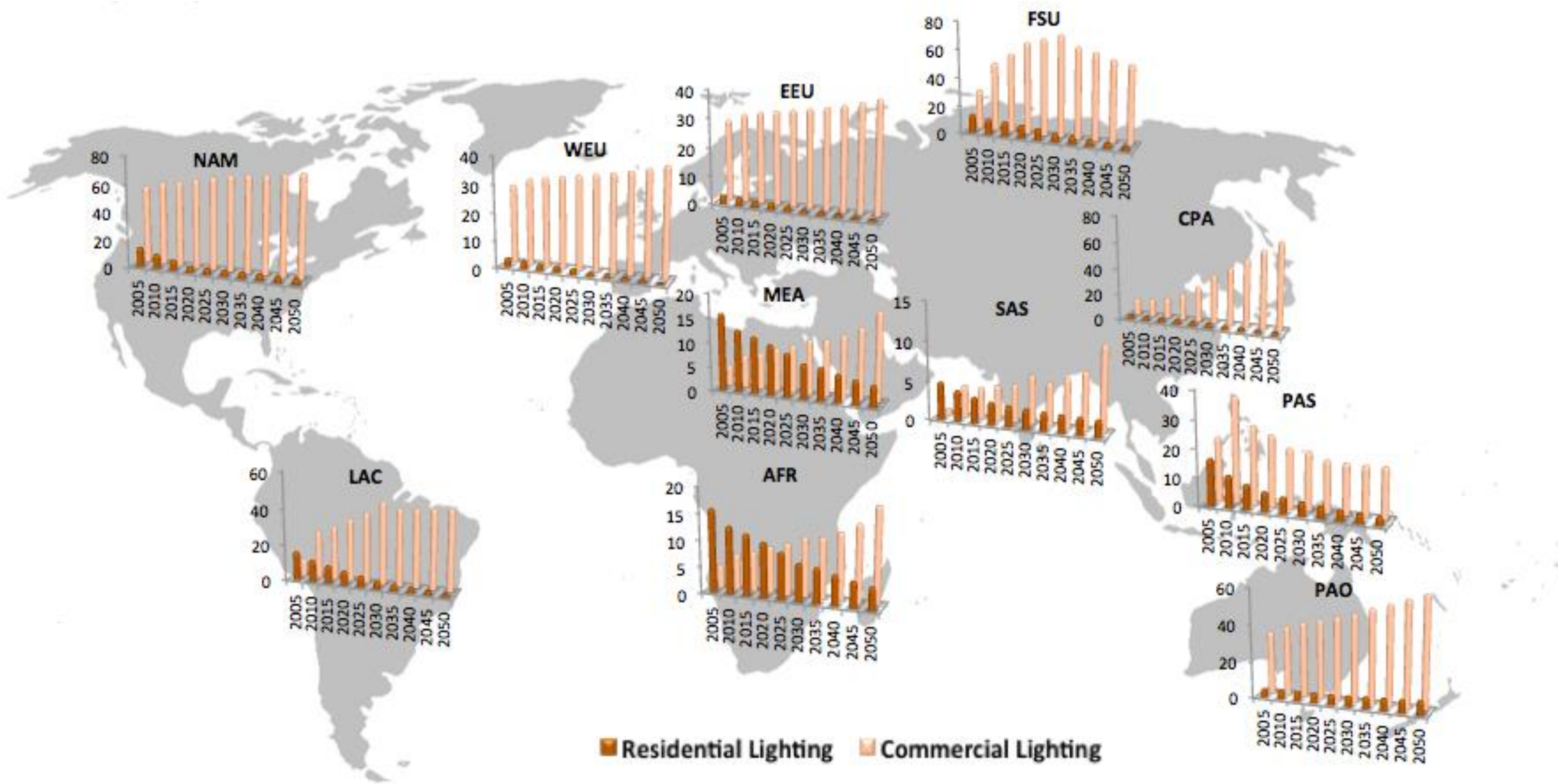



Figure 27. Energy intensities for lighting calculated based on the data from the BUENAS model and aggregated for 11 regions, kWh/m$^2$

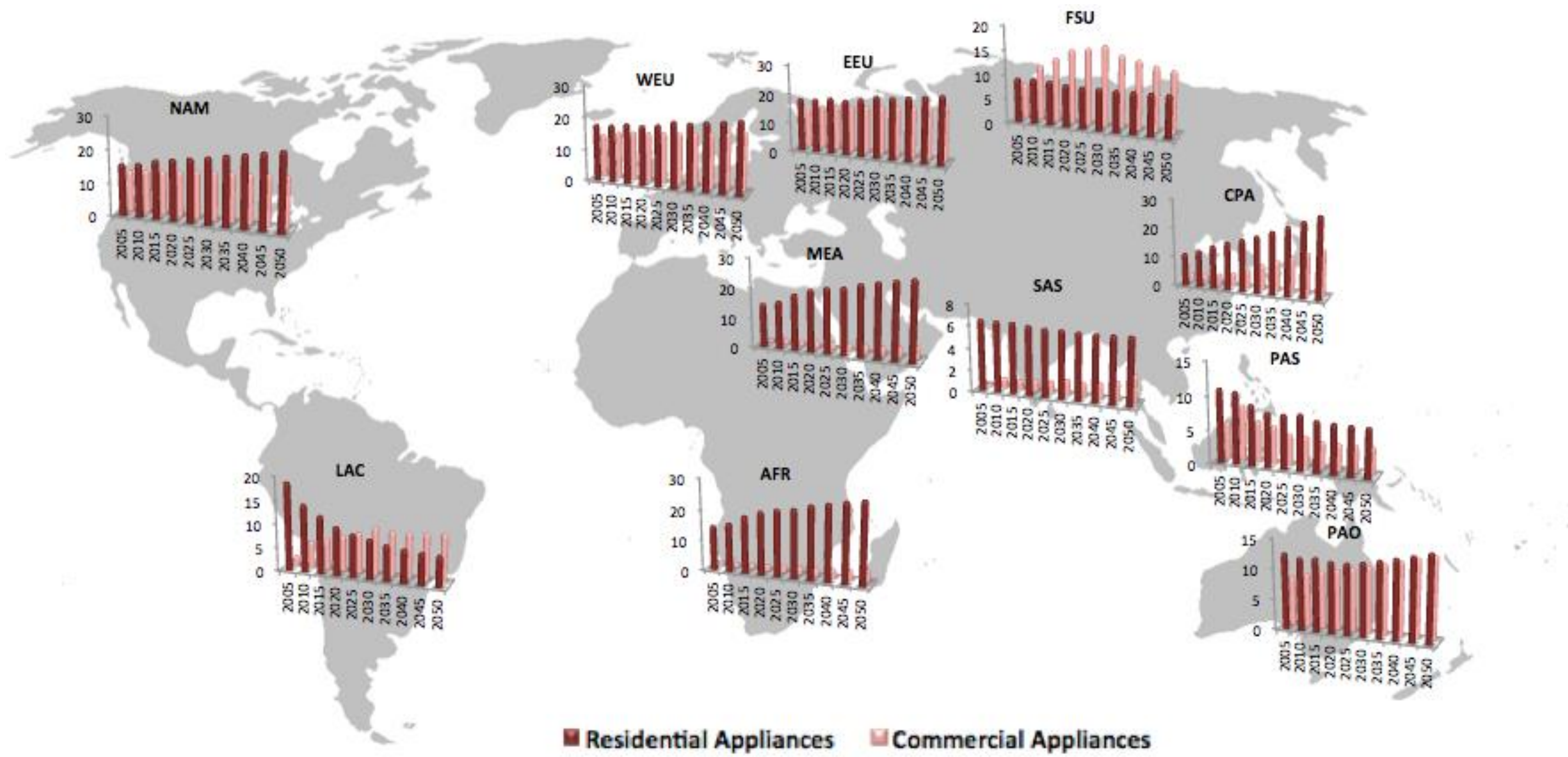



Figure 28. Energy intensities for appliances calculated based on the data from the BUENAS model and aggregated for 11 regions, kWh/m$^2$

# VIII CHAPTER. ANALYSIS OF THE RESULTS ON THE POTENTIAL FOR SOLAR-SUPPLIED NZEBs

This chapter presents the key results for the potential of solar energy produced by building-integrated roof-top hybrid PV/T solar technologies to cover building energy needs.

In this chapter presentation of the results is based on the comparison between energy use and solar energy production in order to conclude to what extent building energy use can be covered by solar energy produced on site.

The discussion of the results in this chapter is structured around ten key messages. Each message is discussed in a separate section presented below. The aims of the messages can divided into three groups: (1) to reflect widely discussed issues in relation to the NZEB concept; (2) to follow from the assumptions made in BISE model; or (3) to present global or regional picture.

The messages included into the first group are related to the timescale for calculating energy balance and determining the NZE status of buildings (Section 0), role of different building types, related building geometry and energy use patterns (Section VIII.2) and climate conditions (Section VIII.4), importance of energy efficiency measures in reducing energy use (Section VIII.3) and importance of short-term energy storage (Section VIII.6) for achieving NZEB goal. Most of these messages were discussed in the literature review presented in Chapter II.

The messages, which followed from some key assumptions made in BISE model include the discussion on the need for energy efficient lighting and appliances (Section VIII.7), influence of building density and shading (Section VIII.8) and roof area availability (Section VIII.9) on the buildings' solar output. These three topics were analyzed by means of sensitivity analysis. Two sections look at a bigger picture: one presents results for developing regions (Section VIII.5) and for the whole world (Section VIII.10).

## VIII.1 Accurate energy balance calculation requires a shorter timescale

**KEY MESSAGE**:
A monthly scale for energy balance calculation offers a higher level of accuracy than the annual one, as it allows for analyzing solar energy coverage of the seasonal energy use peak loads

Determining whether the building is net-zero energy or not significantly depends on the time scale chosen for the calculation of the energy balance (i.e. difference between renewable energy produced/imported in the building and energy consumed to satisfy energy needs) for a particular building. As it was noted in Section II.2.2, the most common time scales for energy balance calculation are a year or a month. However, in many cases buildings, which can have a net-zero energy balance on the annual basis, may not achieve this goal in some months.

This section is exploring the results of the BISE model on the annual and monthly basis. Figure 29 presents estimations for thermal energy use and solar thermal energy generation in all eleven regions considered in this study for the period between 2005 and 2050, while Figure 30 illustrates the results for electric end-uses and potential solar electricity production for the same regions and the time period. Figure 31 and Figure 32 show respective results, but for each month of the year 2050. As Figure 29 shows in all eleven regions solar thermal production exceeds thermal energy use in 2050. However, Figure 31 demonstrates that in a number of regions, such as WEU, EEU, FSU, CPA in the coldest months of 2050 thermal energy needs cannot be covered by generated solar heat to full extent.

As electrical efficiency of the PV/T systems is significantly lower than the thermal one, the amount of potential solar electricity produced is several times lower than that of the solar heat. At the same time electricity consumption is considerable in most of the regions due to high (in case of developed countries) or growing (in case of developing countries) energy intensities for appliances and lighting derived from the BUENAS model. Therefore, in most of the regions even by 2050 solar electricity can cover only certain portion of electrical energy needs. The exceptions are the regions with abundance of solar energy and relatively low electricity consumption, such as SAS, PAS, LAC and AFR. However, if we look at the energy balance by month, for example, during peak demand for cooling in SAS (May and June) solar electrical production cannot meet 100% of energy needs. In other regions the results for years and months are showing similar trends: if the net-zero is not achieved on the annual basis, it is also not achieved in a number of months. For developed regions (NAM, WEU, EEU, FSU, CPA and PAO) it is not possible to cover electrical use with solar electricity in all of the months of the year 2050, however, to a large extent it might be explained by the business-as-usual assumptions of the BUENAS model for the appliances and lighting energy use.

These results demonstrate that the monthly scale for the energy balance calculation is more preferable, as it provides a more detailed understanding regarding building energy demand and potential solar energy supply depending on the climatic and weather variations within the year.

This level of detail is crucial for selecting the technology mix for buildings (e.g. combination of solar technologies with other renewable energy technologies, for example heat pumps, electrical heating back-up, etc.), as well as for sizing up and selecting the type of the solar technologies in order to achieve an optimal combination of solar electric and thermal output in a given building type and climatic conditions.

Figure 29 - Figure 32 present results for the building stock aggregated among different building types. In order to obtain more precise results, it is necessary to look at an energy balance for a particular building type.

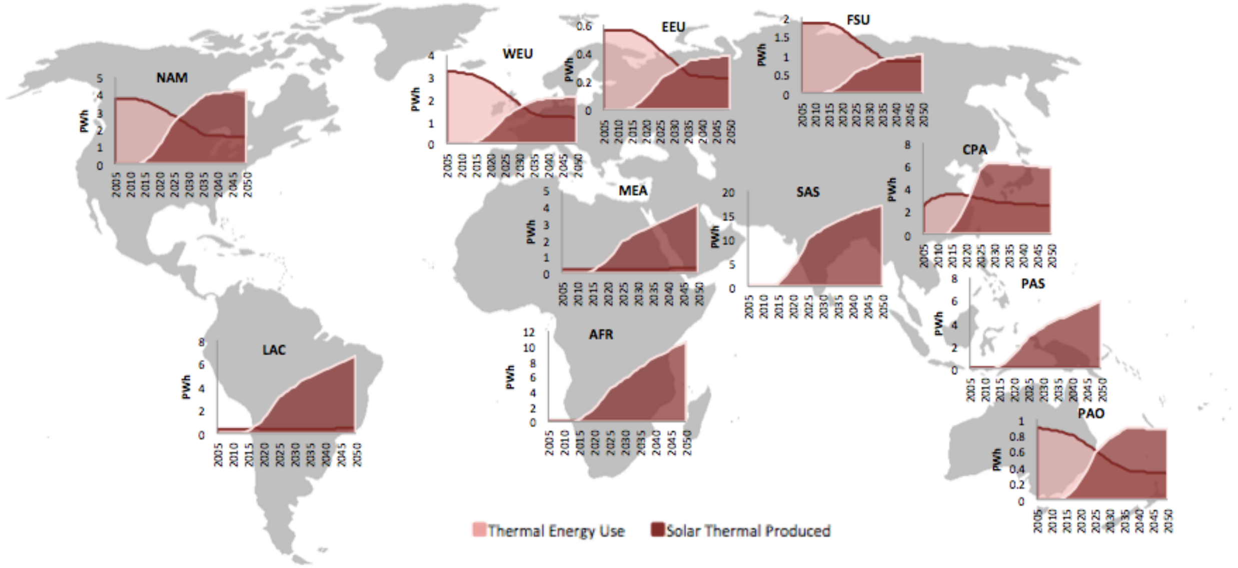



Figure 29. Thermal energy use versus thermal solar energy produced in buildings by year, Deep scenario

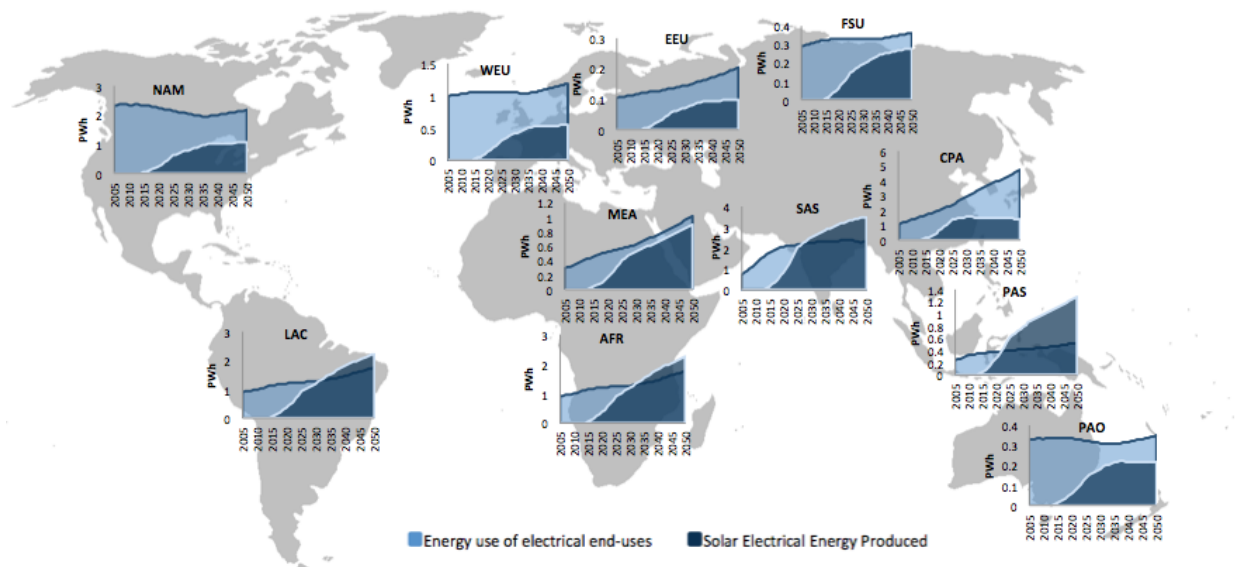



Figure 30. Electric energy use versus electric solar energy produced in buildings by year, Deep scenario

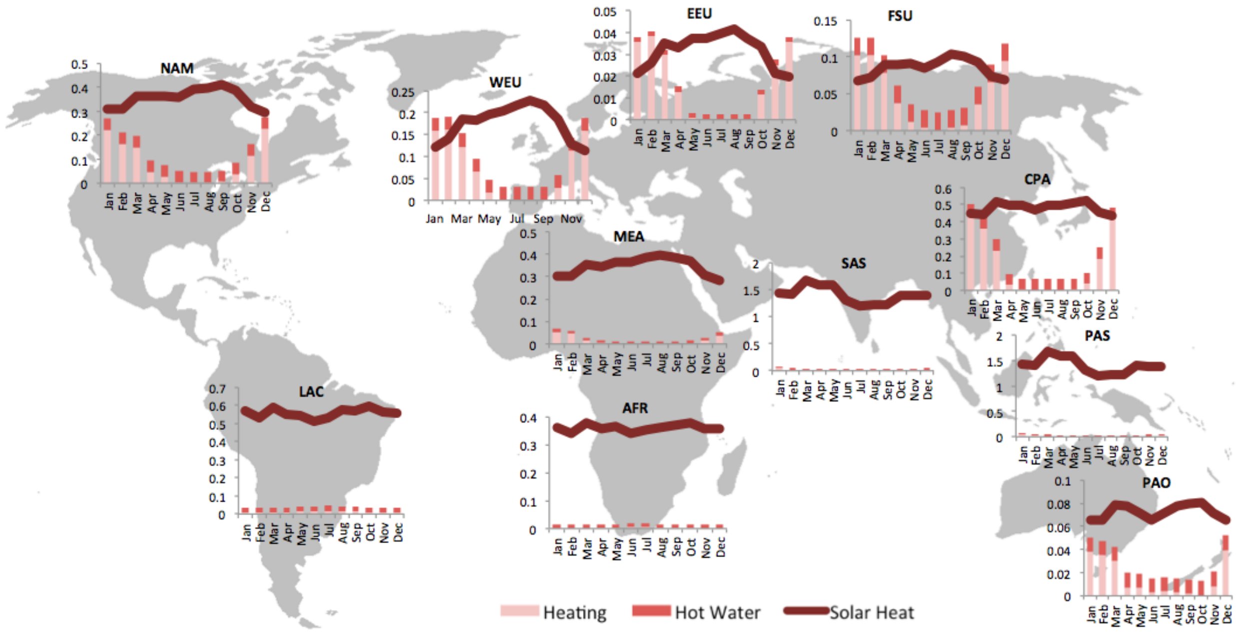



Figure 31. Energy use for heating and hot water versus thermal solar thermal energy produced in buildings by month of the year 2050, PWh, Deep scenario

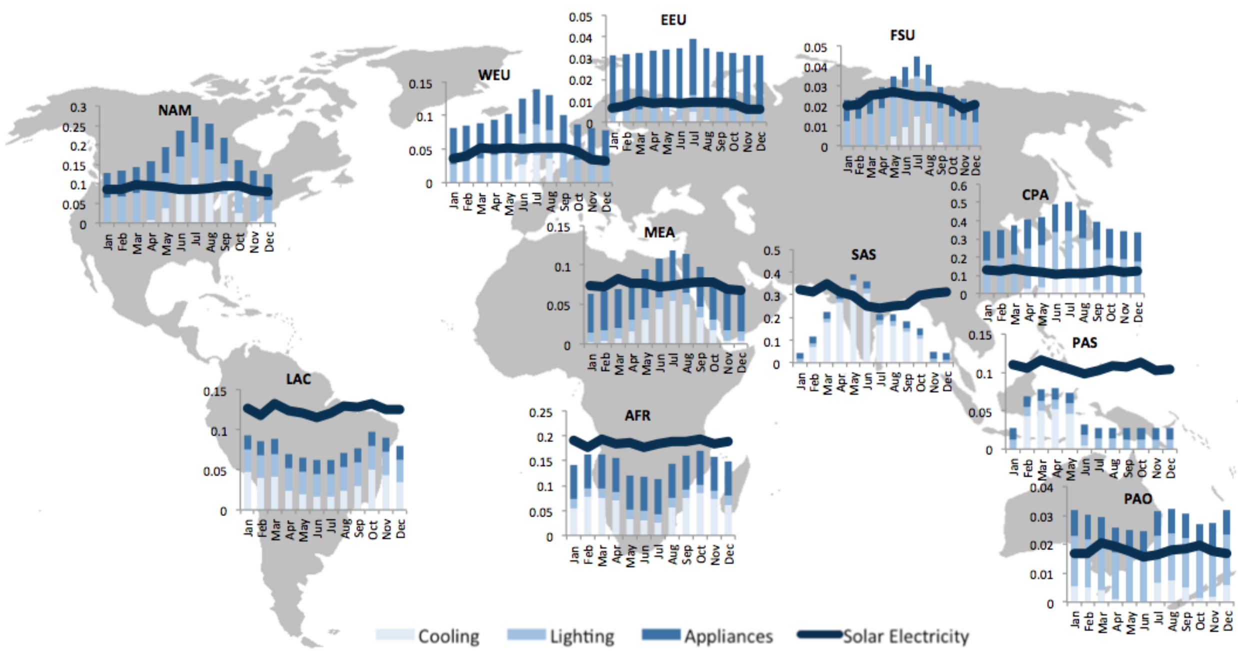



Figure 32. Energy use for space cooling, lighting and appliances versus solar electricity produced in buildings by month of the year 2050, PWh, Deep scenario

## VIII.2 Low-rise buildings have higher potential to achieve NZE goal

**KEY MESSAGE**:
Low-rise buildings have higher potential to cover all energy use by rooftop solar energy production, while in high-rise buildings it becomes impossible due to significantly smaller available roof areas in relation to floor areas.

This section looks at different building types in order to present common trends in the potential of solar energy utilization on the way to net-zero energy buildings. Different building types have different patterns of energy use and different priority end-uses (e.g. in the same region for residential buildings space heating and cooling might be more energy-consuming, while for commercial buildings lighting might be dominating, etc.). Difference in the configuration of the buildings may also have a significant impact on the potential for solar energy production. For example, high-rise buildings, such as multifamily and office buildings, have relatively smaller roof area available for solar technologies installation in relation to the floor area, from which energy consumption is taking place, than low-rise buildings. Therefore, in high-rise buildings it is usually not possible to satisfy all energy needs solely with solar energy.

This hypothesis is supported by the results presented in Figure 33-**Figure 36**.

Figure 33 demonstrates thermal energy use (i.e. sum of energy use for space heating and water heating) and potential solar thermal energy, which can be produced in 2050, for single-family, multifamily and commercial & public buildings. In most of the regions single-family buildings have the highest potential for solar thermal energy generation. For this building type thermal energy needs can be covered solely by solar heat in most of the regions even in the coldest months. The exceptions are December, January and February in the regions like WEU, EEU and

FSU, when energy demand for space heating can be high, but availability of solar energy may be significantly limited due to high cloudiness. Moreover, the performance of solar systems might be restricted under very low air temperatures. Therefore, during these months an additional back up might be needed to satisfy energy needs. However, taking into account that only a few kWh/m2 have to be supplied through the back-up systems, it is likely that there is no need for additional heating systems installations, as it might be possible to achieve through utilization of mobile electric heaters, for example, or other temporary low-energy solutions.

Multifamily buildings in this study are assumed to be located only in the urban areas and are typically high-rise buildings. Therefore, in all regions buildings of this building type have much lower solar thermal potential in comparison to single-family one. However, due to high energy efficiency of the buildings achieved by 2050 under the Deep scenario, in a number of regions building thermal energy needs can be to a large extent satisfied by solar thermal energy even in multifamily buildings as well. Significant need for supplementary space heating is needed in the regions, where heating plays a crucial role during cold months, namely NAM, WEU, EEU and FSU. It has to be noted that in CPA building-integrated solar heat supply is likely be insufficient in multifamily buildings during some months. It is likely to be an important issue especially in heating-dominant climate zones.

Commercial & public (C&P) buildings have lower solar thermal energy potential than that for single-family building in most of the regions. It can be explained by the fact that there are various subcategories within the C&P buildings, which have different heights and, therefore, different roof areas available for the solar energy production. Therefore, when the potentials for various C&P are aggregated, as in in Figure 33, it results in the difference in the solar potentials for C&P buildings. For example, in the regions, where a large portion of C&P buildings are high-rise (e.g. NAM, CPA, MEA, etc.) the potential for solar thermal energy generation is much lower than that of the single-family buildings, while for the regions (such as PAS, WEU, PAO, etc.) where typical C&P buildings are lower in heights, this potential (on the kWh/m$^2$ basis) is much closer to the one for the single-family buildings. However, as these results are aggregated among different C&P sub-categories, in order to receive a more precise picture it is necessary to look at the thermal energy balance for each sub-category.

Solar thermal potential and its ability to cover thermal energy use in different C&P sub-categories are presented in Figure 34. This figure shows that retail buildings can produce the highest amount of energy (as they have the largest roof-to-floor ratio), while office building have the lowest potential, as they assumed to be the tallest in all the regions. As the deep scenario assumes significant reduction in space heating and water heating energy use by 2050 through energy efficiency improvements, the specific energy consumption for these end-uses is relatively low for most of the C&P sub-categories, which makes it possible to cover a significant portion of these energy use with solar heat.

In the regions, like PAS, SAS, AFR, LAC, PAO, MEA, thermal energy needs can be met by solar in all C&P building sub-categories. In the regions, where solar resources are more limited, this can be achieved during only some months and not for all building sub-categories. For example, office buildings require additional technologies for heating for up to 5 months in the regions like NAM, FSU, EEU, etc. The trends in the thermal energy balance for the office buildings are similar to the ones for the multifamily buildings described above.

Electric use and potential solar electricity generation in 2050 for different building types are presented in **Figure 35**. It can be seen that the picture for electric use is much more diverse among regions than is case of the thermal energy.

As for residential buildings, in a similar manner as with solar thermal energy, solar electric potential is higher in single-family buildings than in multifamily due to the same reasons described above. Therefore, in a number of sunny (and usually developing) regions, such as LAC, AFR, PAS, CPA, SAS, 100% of electrical energy use can be covered in all months in single-family buildings. In other regions, such as NAM, WEU, EEU, FSU, PAO, solar electricity is not sufficient for the full coverage of the electric energy use during the hottest months. It is mostly caused by the peak demand for space cooling. As the amount of excess electricity is not very high and usually takes place only in 1-3 months during the year in most of the regions, it might be solved through application of mobile technologies (such as fans or ventilators) or even through natural ventilation.

Different situation is illustrated for multifamily buildings: in most of the regions solar electricity generated on the building site is not sufficient for meeting electrical energy use for a number of months. In all developed regions (such as NAM, WEU, EEU, FSU, PAO), as well as in some developing ones (AFR, CPA, MEA) solar electricity is not sufficient for multifamily buildings during all the months of the year. On one hand, it can be explained by limited available roof area for solar technologies in multifamily buildings in relation to the floor area, on the other, - high level of energy intensities for residential appliances, assumed under the business-as-usual scenario of the BUENAS model for a number of regions (see Section VII.3).

Electric use in C&P buildings is usually higher than in residential buildings. It can be mostly explained by relatively larger energy intensities for lighting in commercial buildings coming from BUENAS model. Therefore, as **Figure 36** shows that in most of the regions solar electricity is not sufficient for covering electrical energy use in the majority of C&P sub-categories. Example of exceptions can be AFR and PAS, where electrical energy use can be covered in almost all months for all sub-categories, except office buildings. In SAS only peak-cooling demand cannot be covered solely with solar, while for other months on-site solar electricity production can be sufficient for most of the building sub-categories.

Figure 37-Figure 40 give the opportunity to have a closer look at thermal and electric energy use versus potential on-site generation of solar heat and solar electricity in 2050 for different building types and for four regions: NAM, WEU, CPA and SAS under Deep scenario. The figures also provide the split of energy use by end-use. **Figure 41-Figure 44** illustrate the same kind of results and for the same regions, but by C&P sub-category. Results for other regions can be found in Annex E, Section XV.1.

In can be seen that in North America all building types consume approximately the same amount of total thermal energy, however, the share of energy for water heating is slightly smaller in commercial and public buildings in comparison to the residential ones. The picture for electrical energy use is different: C&P buildings have much higher energy consumption, mostly due to higher lighting energy intensities. Energy use for cooling is relatively low in all building types, which is due to ambitious energy efficiency improvements assumed under the Deep scenario.

As for the solar energy generation, single-family buildings have the highest potential, followed by C&P and then multifamily buildings. However, the amount of solar electricity produced by square meter of floor area is typically about 3 times lower than that of solar thermal energy due to differences in system's efficiencies.

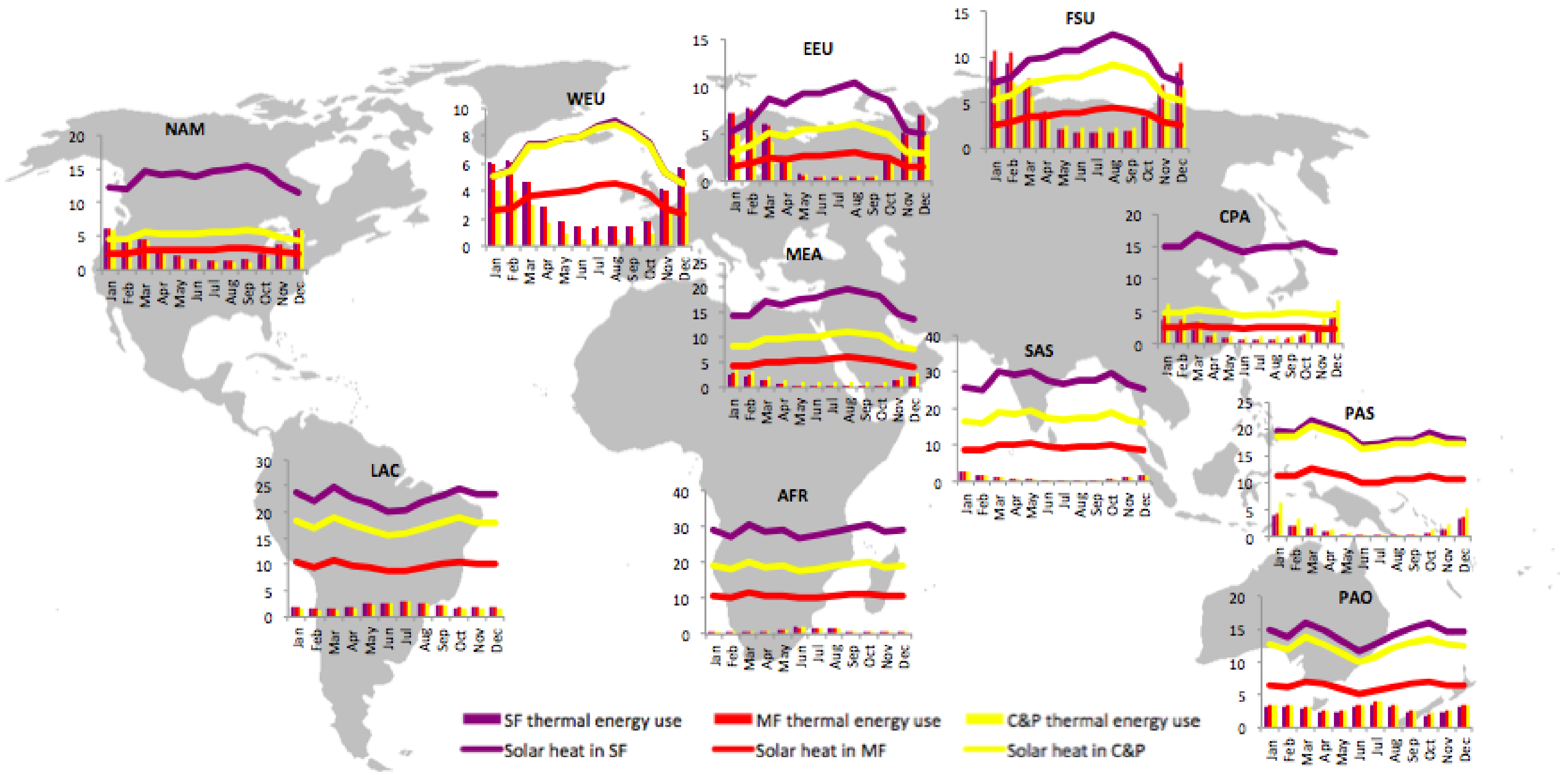



Figure 33. Thermal energy use versus thermal solar energy produced in 2050 by building type, kWh per m$^2$ of the floor area

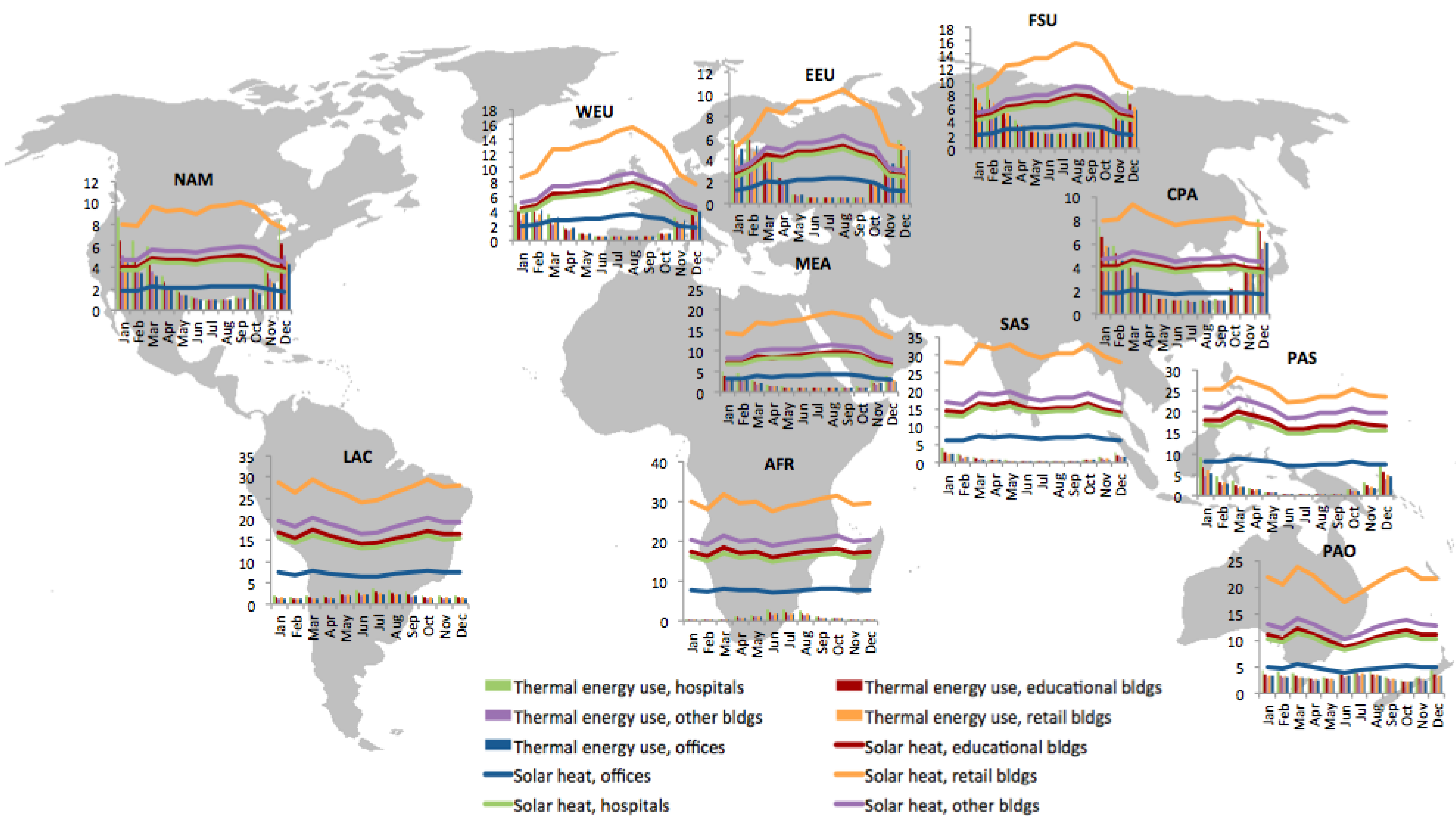



Figure 34. Thermal energy use versus thermal solar energy produced in 2050 by commercial building category, kWh per m$^2$ of the floor area

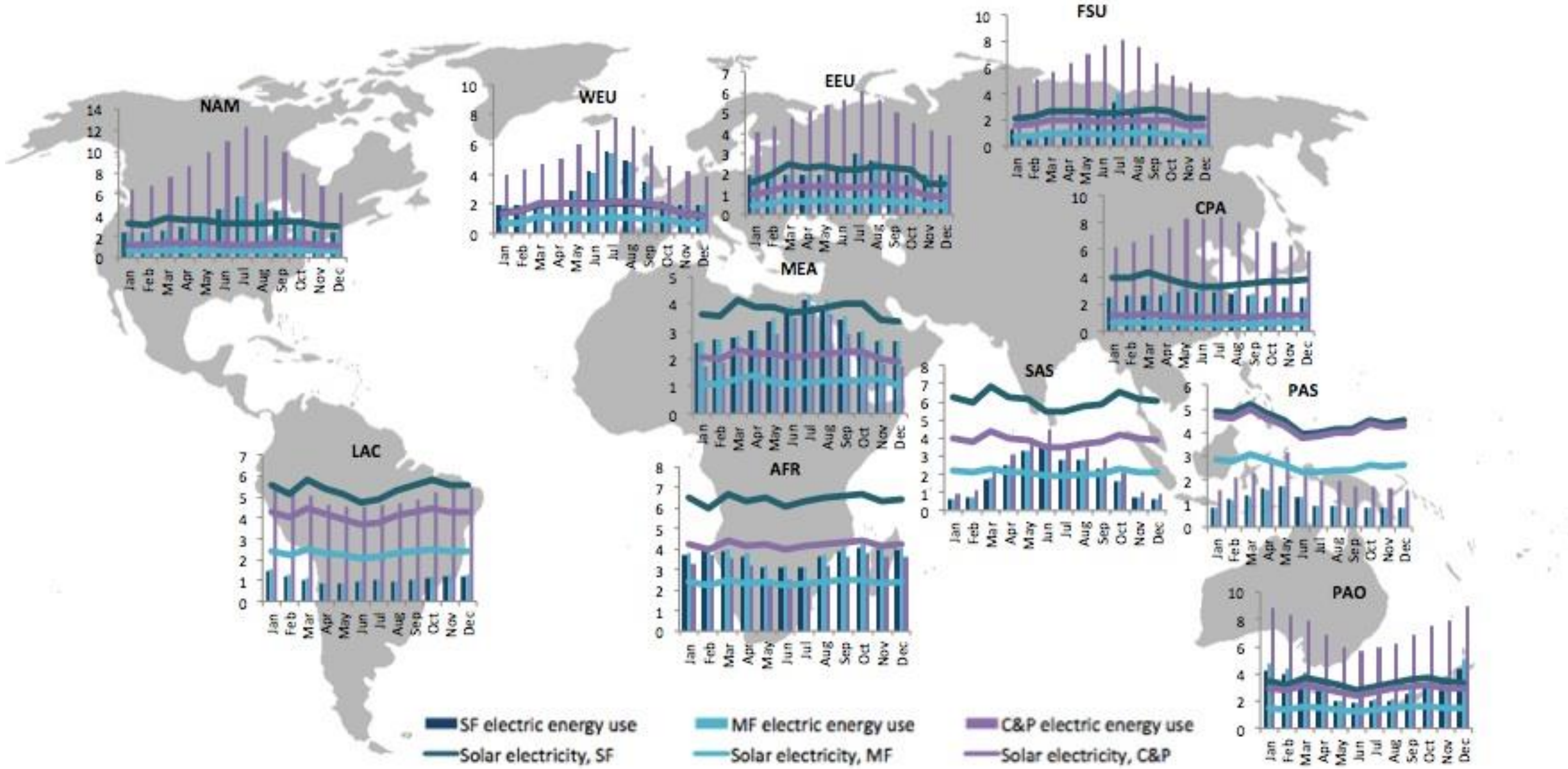



Figure 35. Electric energy use versus electric solar energy produced in 2050 by building type, kWh per m2 of the floor area

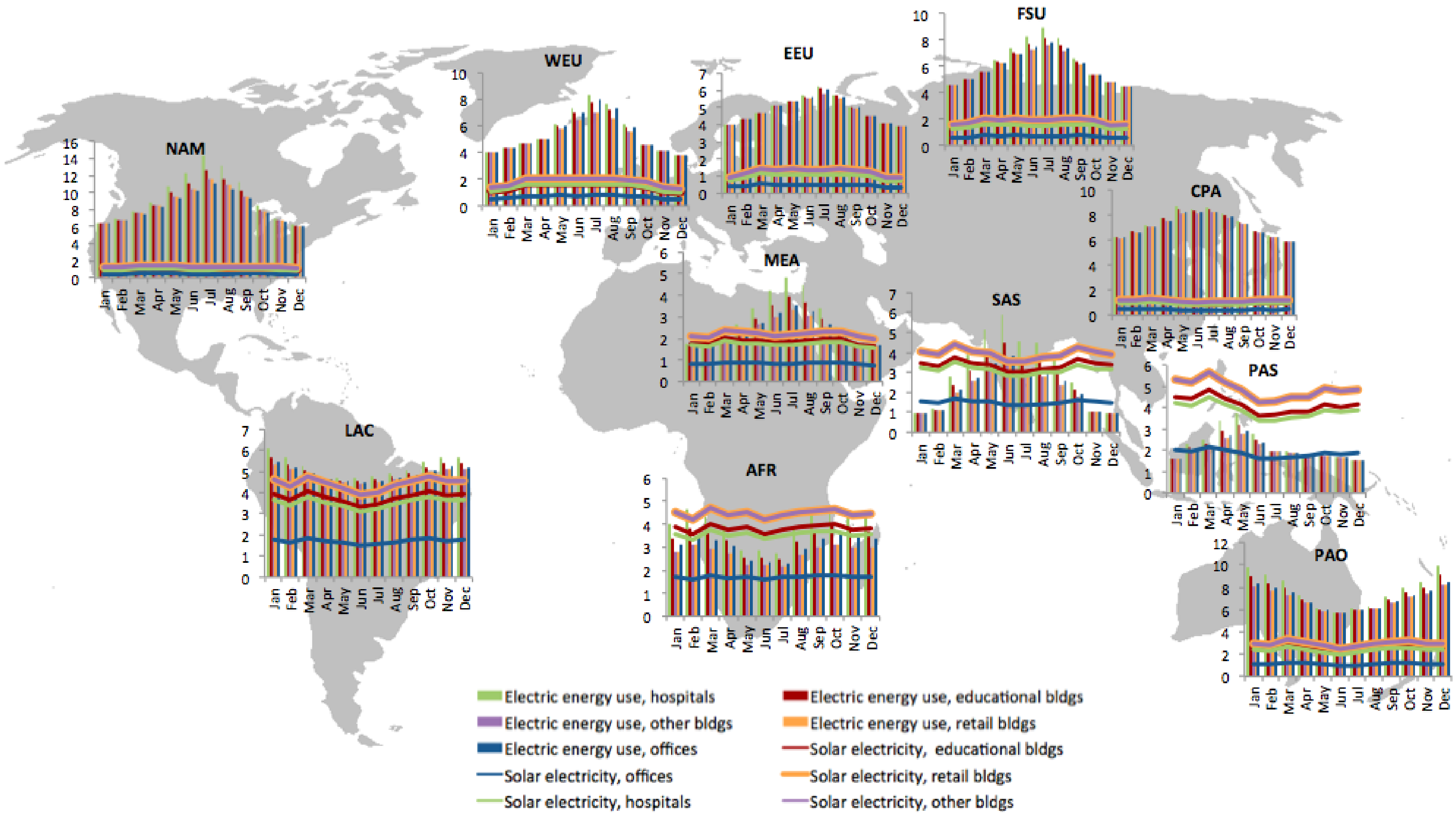



Figure 36. Electric energy use versus electric solar energy produced in 2050 by commercial building category, kWh per m2 of the floor area

As Figure 37 shows in NAM region building-integrated solar generation can help to achieve net-zero energy goal throughout all months only in single-family buildings. However, even for this building type some back-up electricity supply may be needed during the summer months due to extensive cooling needs. As for commercial and multifamily buildings other sources of electricity supply are needed throughout the whole year. In commercial buildings more efficient lighting strategies are highly recommended in order to reduce respective electricity consumption. Generally, for (high-rise) multifamily and C&P buildings the opportunity to generate sufficient amount of renewable energy on site is significantly limited. Figure 41 further confirms this statement: as for office buildings, which are usually the tallest ones, both solar thermal and electric energy are not enough to cover energy use in a number of months, while buildings with more modest heights, like hotels & restaurants or retail ones, have higher solar potential, at least for the thermal part. Solar electric supply, however, requires substantial back-up for all C&P sub-categories.

Figure 38 and Figure 42 demonstrate considerable solar potential in South Asia, which is the highest among four analyzed regions. In all building types and C&P sub-categories solar thermal energy supply exceeds energy use by several times during all the months. Solar electricity can also be sufficient to meet building needs in electricity in a number of building types and sub-categories, such as single-family, hotels & restaurants (with exception for a small portion of June's energy demand), retail and other buildings. In other building types electricity needs can be met by solar energy during 4-6 months of the year.

Higher potential for solar net-zero energy in SAS can be explained, on one hand, by the abundance of solar energy resources and, on the other, by relatively lower energy intensities for lighting in C&P buildings than in developed regions.

The fact that high amount of solar thermal heat produced over the year is excessive may indicate that this kind of a solar system is not optimized for the local climatic conditions. Therefore, it may make more sense in hot and sunny climates (not only in SAS, but in other regions as well) to install other types of PV/T systems with higher electric efficiencies and lower thermal output. As alternative or complimentary solution a solar cooling might be considered, when the solar PV/T system is coupled with an absorption chiller to provide space cooling during hot period of the year. This way solar electricity is likely to be sufficient to cover electricity use for appliances and lighting in all building types.

In case of the oversupply of the solar electricity the excess can be fed into the grid in case of the grid-connected buildings, which might make these buildings energy positive. A supplementary strategy can be partial shading of the solar systems during summer months. Moreover, at the scale of the individual buildings the size of the system should be very well thought through. Under the assumptions for estimating the maximum technical potential introduced in this study the solar systems maybe oversized for some building types (e.g. single-family buildings). However, in the global model presented in this study it was not possible to consider this kind of factors, which have to be tackled for each individual building.

A similar situation to the one described for NAM can be seen in **Figure 39** for Western Europe. Solar potential in WEU single-family buildings is slightly lower than in NAM, which can be explained by the difference in the climatic conditions: in NAM larger area of the region is located in lower latitudes with larger number of sunny days than in WEU. As for multifamily buildings, results for WEU show a bit higher potential, which is due to typically lower buildings of this type than in NAM.

Noticeable difference between WEU and NAM can be seen in the higher solar potential in WEU's C&P buildings. In this building type in WEU solar thermal energy can be sufficient to cover respective demand in every month. However, thermal energy needs not of every C&P sub-category can be met solely with solar. **Figure 43** shows that during cold months (November – February) it will be hard to cover 100% of heating demand with solar heat.

As for solar electricity, its potential is also limited in commercial sub-categories, however, it can cover larger portion of the energy use than in NAM. It can be explained by lower heights of European commercial buildings, as well as more efficient lighting than in the North American region.

Centrally Planned Asia demonstrates a relatively high solar potential (higher than in NAM and WEU, but lower than in SAS). **Figure 40** shows that net-zero energy goal is likely to be achieved for single-family buildings, meaning that both thermal and electric energy needs can be satisfied with solar energy. For this building type in CPA region the problem of excess heat is also topical. It can be tackled in a similar manner as in SAS, for example, by reducing the size of the system, introducing shading of the systems during summer months and using part of the solar heat for cooling.

Solar thermal energy supply can play an important role for multifamily buildings as additional heating sources are only needed during the coldest months (December - February). Moreover, CPA has a quite diverse climate and, therefore, in warmer climate zones the situation may be even more favorable. The importance of different climate conditions will be discussed in Section VIII.4. However, solar electricity is unlikely to be sufficient for covering all electrical needs in multifamily buildings. Residential buildings in CPA are assumed to have quite significant energy intensities for appliances by 2050, which for multifamily buildings will result in the need for additional sources of electricity.

A number of C&P sub-categories in CPA demonstrate good coverage of thermal energy needs with solar: usually alternative solutions are needed only during 2-4 months. In case the remaining energy demand is not very significant (e.g. as in educational buildings and hotels & restaurants), the problem is likely to be solved by mobile electrical heaters or other low-cost temporary options. Satisfaction of the electricity demand in C&P buildings, on the other hand, requires more substantial interventions, as the portion, which can be covered through utilization of solar energy is rather small for all sub-categories.

The results discussed above clearly show the necessity to consider building type, when setting a net-zero energy goal. Moreover, it is important to take into account building types, when choosing a certain definition for net-zero energy buildings.

For example, for single-family buildings it can be technically feasible to achieve net-zero energy status by using only building-integrated technologies. Moreover, it is possible that even a single technology (e.g. solar PV/T system) might be sufficient to satisfy both thermal and electric energy needs. However, for high-rise buildings (e.g. multifamily or office buildings) it is very likely that building-integrated solar technologies will not supply enough energy and, therefore, they have to be combined with other technologies or the boundaries of the renewable energy supply should be extended beyond an individual building (e.g. community or district).

The results show that it is very unlikely to achieve net-zero energy status in high-rise buildings using only on-site technologies. Electricity use is significant in commercial and public buildings and the amount of the energy produced on the limited roof areas will not be sufficient for covering this demand. Even if other on-site renewable technologies are used, for example, building-integrated wind mill, it is unlikely to supply enough electricity. The cost of such installation together with PV/T system will be considerable. Moreover, in the urban highly-dense build-up areas, it might not be technically possible to install wind-mills on building sites. However, this technology is not considered in this dissertation and requires further research.

Therefore, the definition for high-rise buildings should account for the import of renewable energy from other places than building site. It can be the territory of the community or district, where excess amount of produced renewable energy can be imported to the buildings in need, or special facilities, like solar or wind plants, which can supply the required amount of renewable energy through the grid.

At the level of an individual building the design and size of the solar technology should be optimized, according to the building's geometry, energy use profile, climate conditions and many other factors, which is not possible to account for to full extent in a global model.

BISE model in this study does not directly deal with the excess solar heat, which might be produced during summer months, especially in the hot regions. However, a number of strategies can be considered to tackle this problem, such as down-sizing the solar system, shading some parts of the systems, introducing solar cooling or efficient storage systems.

Moreover, it is necessary to take into account climate zone, in which the building is located, as the energy balance may vary significantly for different climate zones even within one region. It will be discussed in more details in the following section.

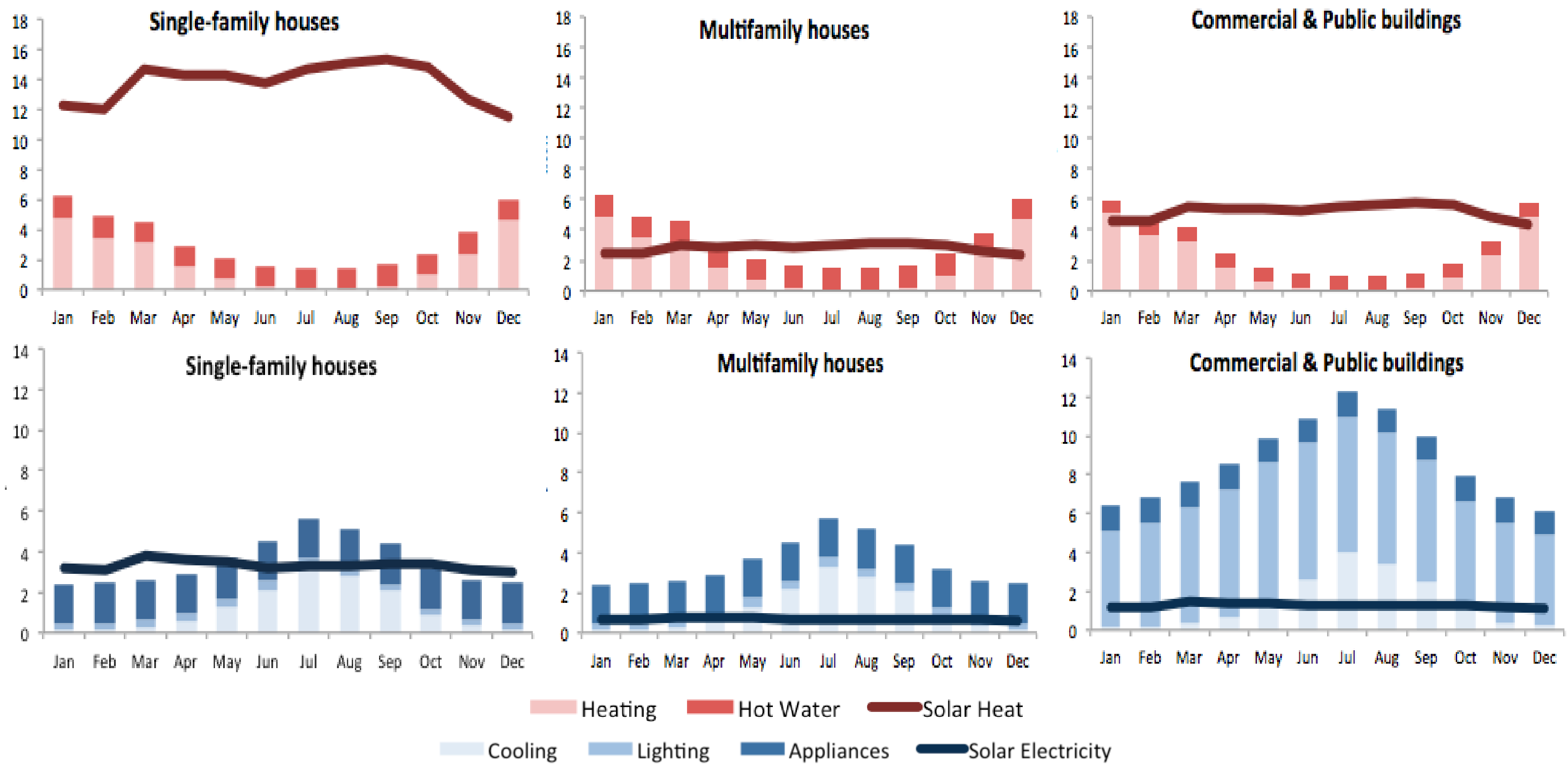



Figure 37. Energy use for different end-uses vs solar energy production in 2050 by building type, kWh per m2 of the floor area, North America, Deep scenario

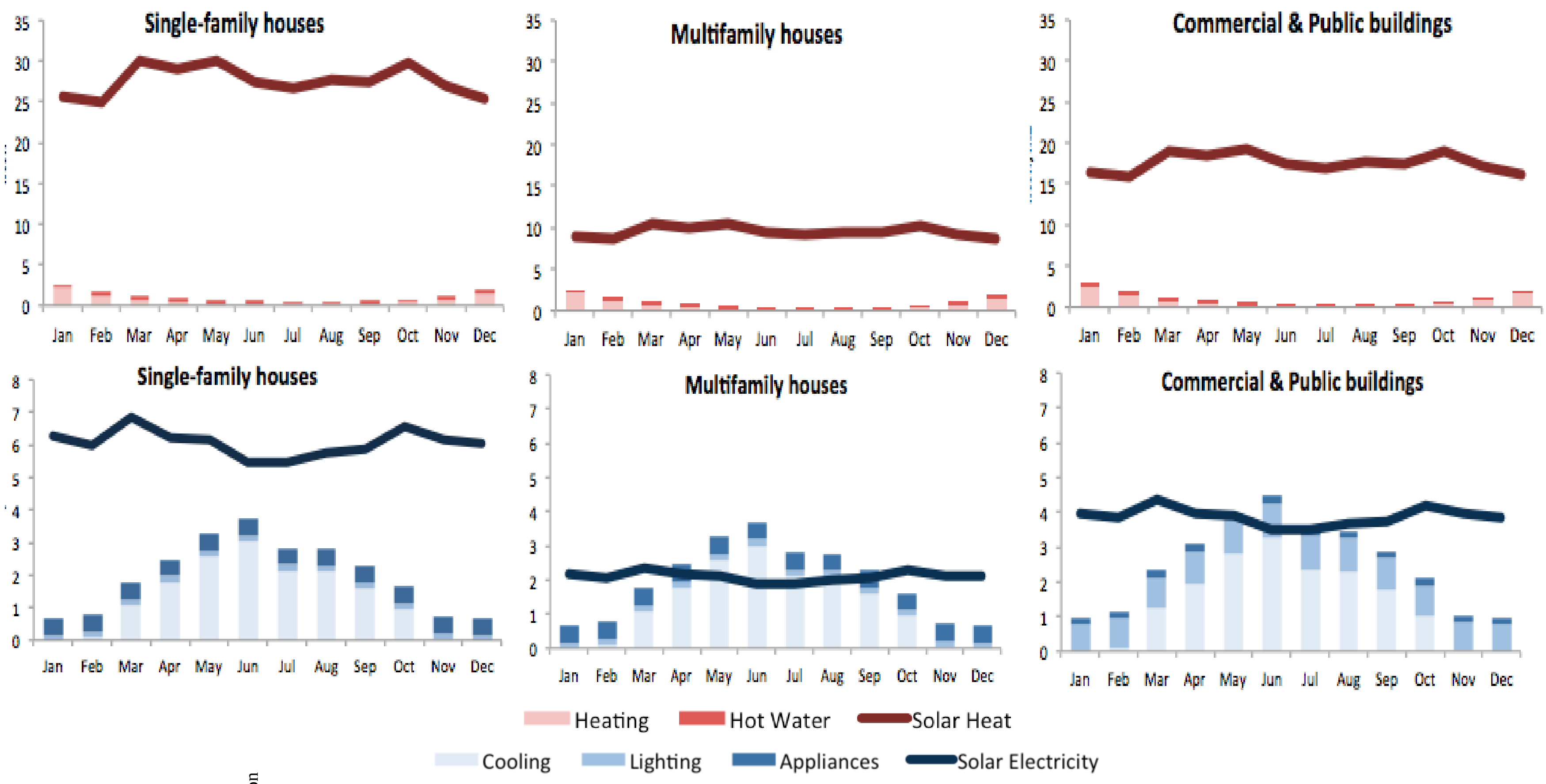



Figure 38. Energy use for different end-uses vs solar energy production in 2050 by building type, kWh per m2 of the floor area, South Asia, Deep scenario

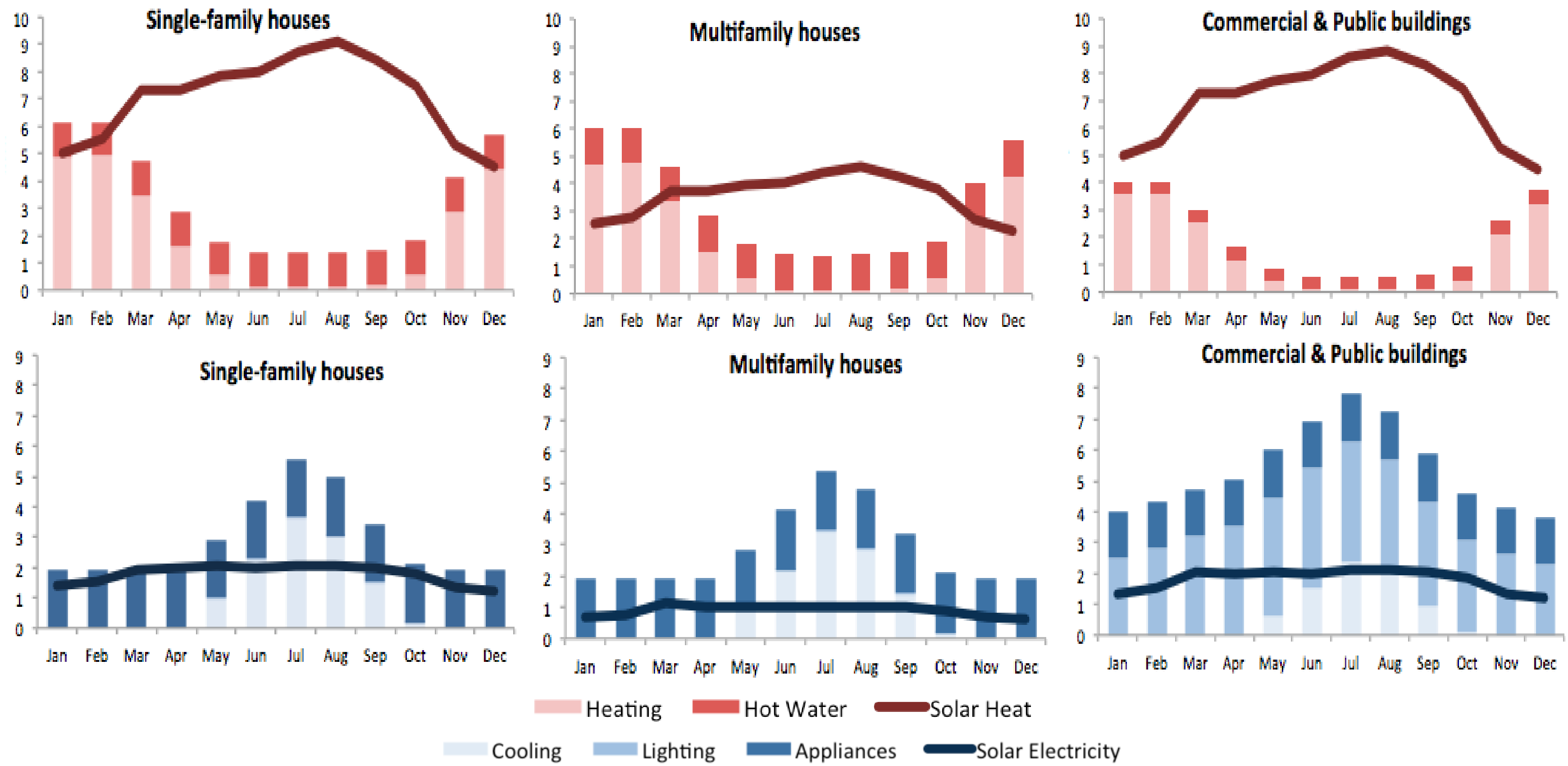



Figure 39. Energy use for different end-uses vs solar energy production in 2050 by building type, kWh per m2 of the floor area, Western Europe, Deep scenario

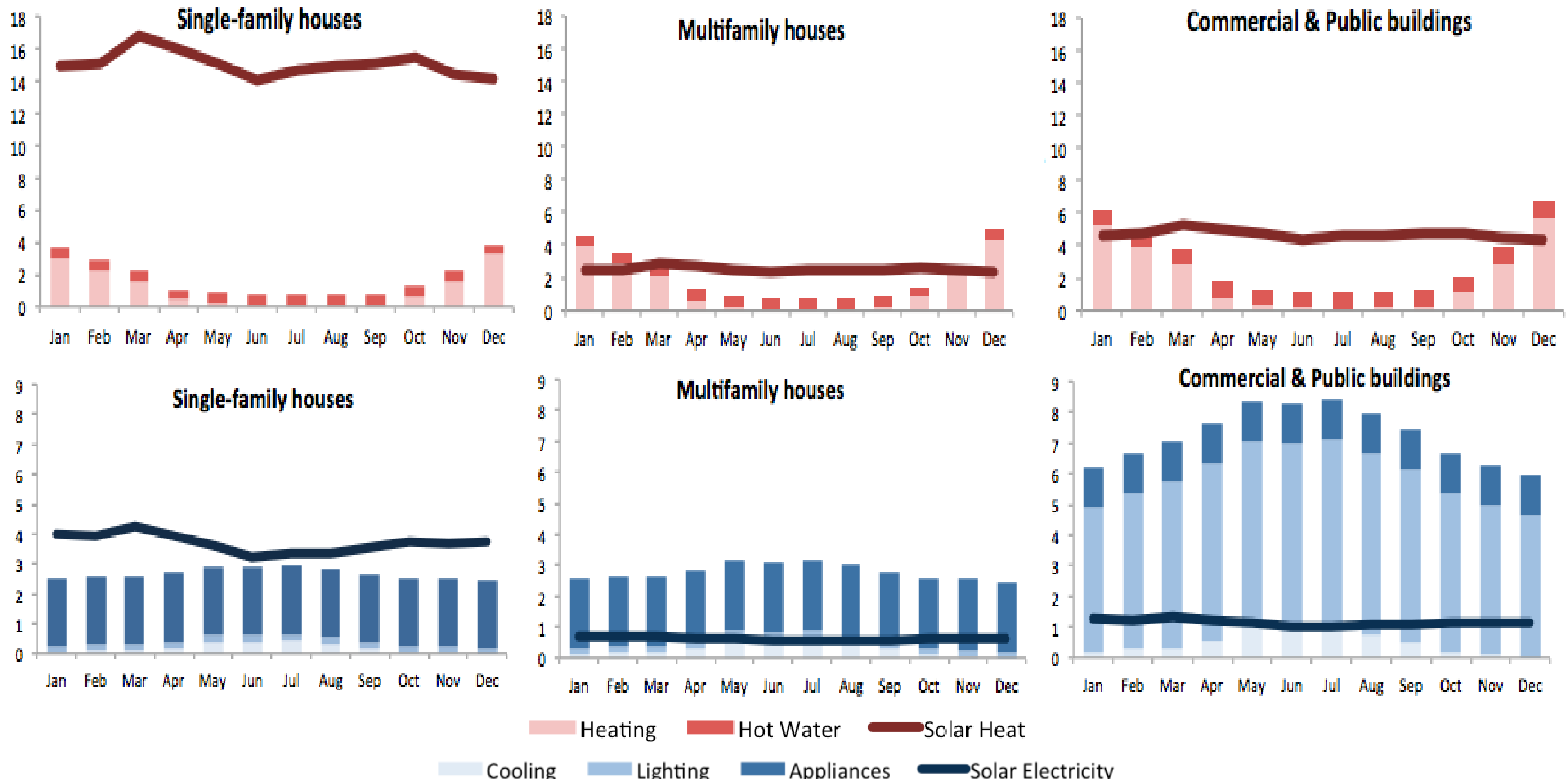



Figure 40. Energy use for different end-uses vs solar energy production in 2050 by building type, kWh per m2 of the floor area, Centrally Planned Asia, Deep scenario

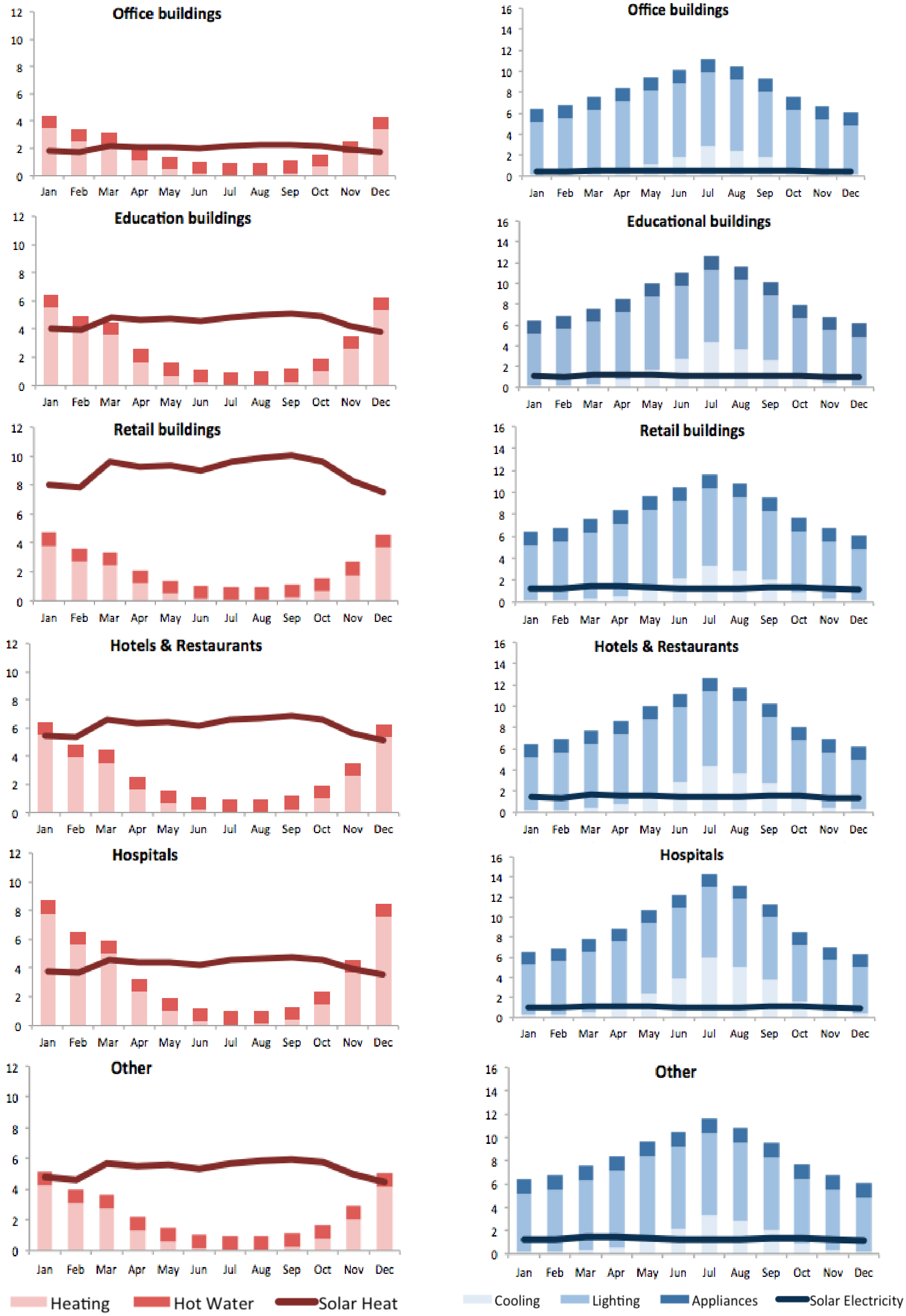



Figure 41. Energy use vs solar energy production in 2050 by C&P sub-category, kWh/m2 of floor area, NAM, Deep scenario

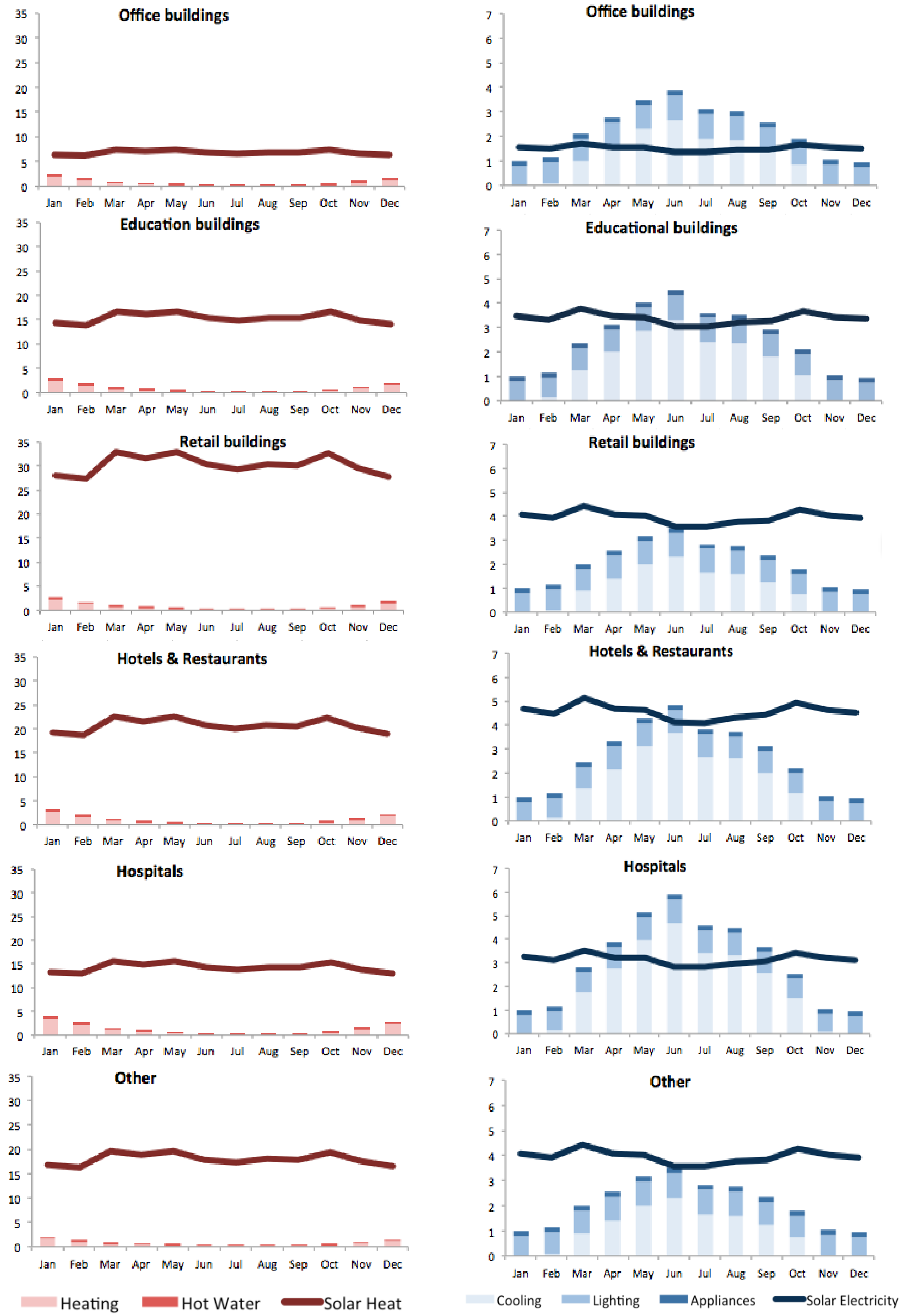



Figure 42. Energy use vs solar energy production in 2050 by C&P sub-category, kWh/m2 of floor area, SAS, Deep scenario

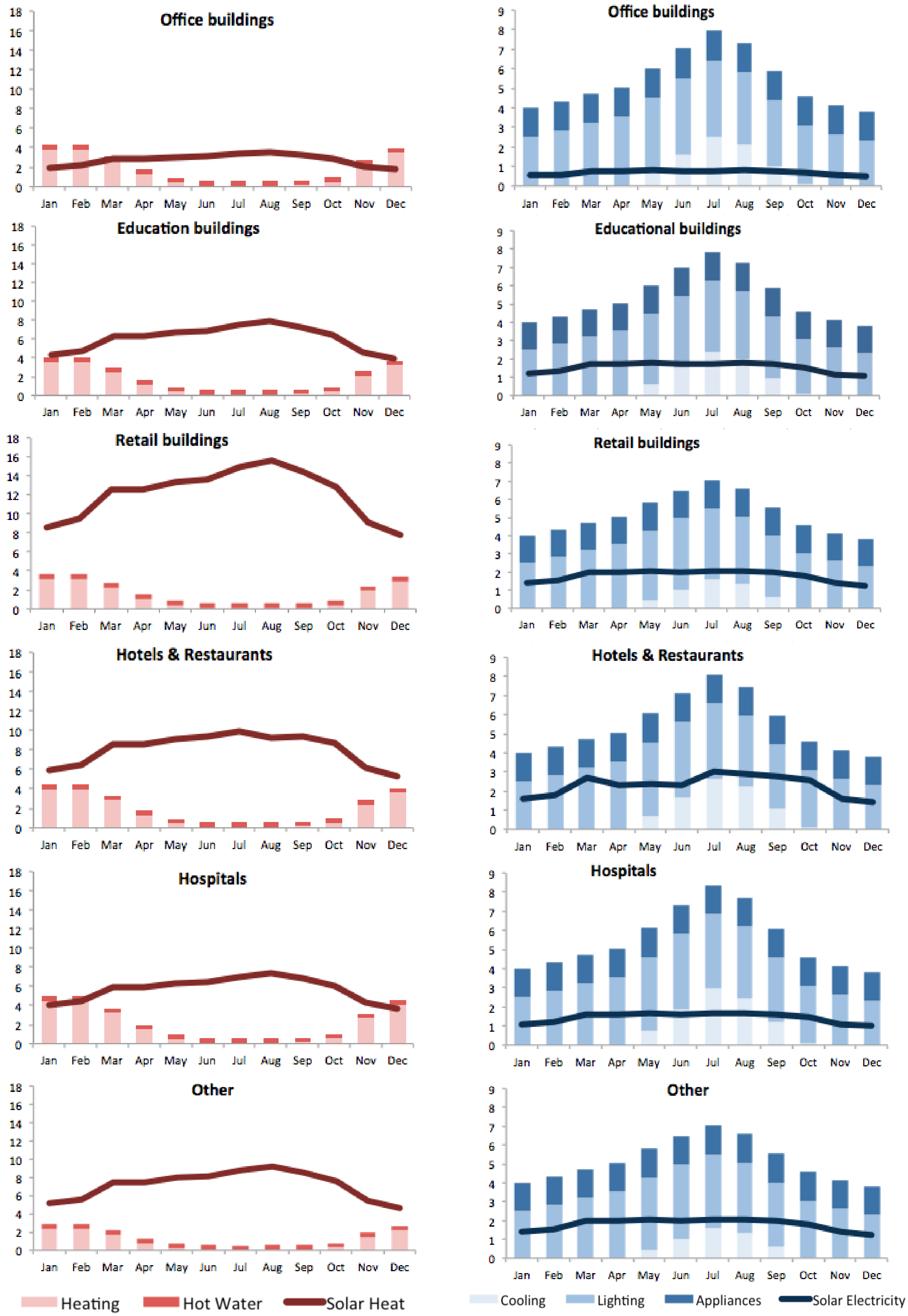



Figure 43. Energy use vs solar energy production in 2050 by C&P sub-category, kWh/m2 of floor area, WEU, Deep scenario

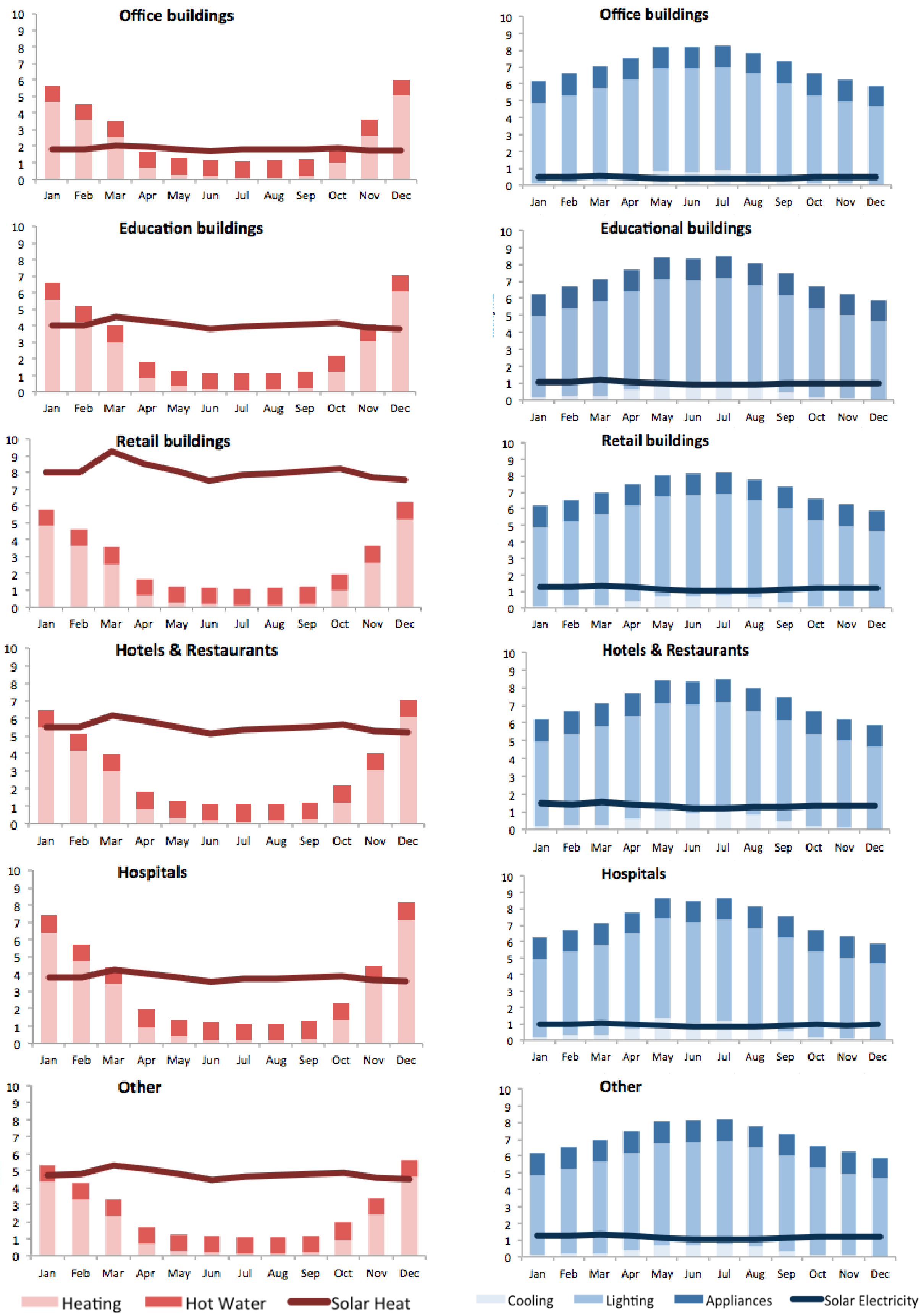



Figure 44. Energy use vs solar energy production in 2050 by C&P sub-category, kWh/m2 of floor area, CPA, Deep scenario

## VIII.3 Energy efficiency plays a crucial role in NZEBs

**KEY MESSAGE**:
High level of building's energy efficiency plays a major role in achieving the NZE status and should be an essential requirement for any NZEB in order to avoid oversizing of the renewable energy systems and overexploitation of energy resources.

As it was discussed in Chapter II improvement of energy efficiency is a crucial step on the way to achieving a net-zero energy status of a building. Once energy demand is significantly reduced through energy efficient measures, remaining energy needs have to be covered from renewable energy sources. Following this logic for the building energy balance analysis this study is using the results for energy use from the Deep scenario of the 3CSEP-HEB model, which presumes ambitious proliferation of energy efficient best-practices for space heating, space cooling and water heating.

In this section the importance of energy efficiency for net-zero energy building is illustrated through the comparison of energy balances using the results for energy use for space heating, space cooling and water heating under Deep and Moderate scenarios. Such an analysis gives the opportunity to compare how much of building energy use in different building types can be covered in the situation of very ambitious energy efficiency improvements (i.e. Deep scenario) to the case of moderate building energy performance, which can be achieved by 2050, if the present policy trends are followed (i.e. Moderate scenario).

Table 27 - Table 30 present summary results on the potential coverage of energy use in building by solar energy during the year 2050. The tables show that under Moderate scenario the chances to achieve the net zero energy goal in most of the building types are much lower than under the Deep one. Tables also show the difference in the potentials between developed and developing regions with clear advantage of the latter ones.

As Table 27 and Table 28 show that in developing regions (SAS, PAS, MEA, LAC, AFR) there is a very little difference between the scenarios in case of thermal energy use: under both scenarios in most building types thermal energy needs can be satisfied throughout the year solely with solar heat supply (except for 4 building types in MEA, offices and hospitals in PAS and SAS under the Moderate scenario).

As for developed regions, 100% of coverage in all months can be achieved only in certain building types, for example, retail building in all the regions or single-family buildings in NAM, PAO and CPA. Multifamily and office buildings demonstrate the lowest potential for coverage among other building types in developed regions: depending on the region there are 3 to 8 months in these building types, when solar thermal is not sufficient. PAO demonstrates the largest potential among developed regions for meeting thermal energy demand with solar: under the Deep scenario 100% coverage of thermal energy use can be achieved during all months and in all building types.

Results for the Moderate scenario (Table 28) clearly show that the number of months, where thermal energy needs require additional energy sources besides on-site solar energy generation, increase significantly, at least for developed regions. In these regions most of the cases, for which under the Deep scenario 100% coverage is possible for all 12 months, in the Moderate scenario will have several months, when it will not be possible. Only five building types of PAO, single-family buildings in CPA and retail building in WEU, demonstrate the possibility to cover thermal energy use with solar in all months under the Moderate scenario.

Developing regions have sufficient solar resources to cover thermal energy needs with solar heat throughout the year in all building types, even with the moderate building energy efficiency. However, there are also several exceptions, like office and hospital buildings in SAS, PAS and MEA, as well as MEA multifamily and educational buildings, which have several months, during which solar thermal energy might not be sufficient.

As for electrical energy (Table 29 and Table 30) the difference between scenarios is more obvious in developing regions, as in most building types (except for single-family buildings) of the developed ones electric energy use cannot be covered in all the months under both scenarios. In some developing regions for some building types the potential for getting to the net-zero is quite high. Under the Deep scenario both thermal and electric energy use can be covered in all months for single-family buildings in PAS, SAS, AFR and LAC, for multifamily buildings in PAS and LAC, as well as for retail buildings, hotel & restaurants and other building category in PAS, SAS and AFR. However, under the Moderate scenario most of these opportunities will be lost. Only single-family buildings in PAS and LAC and several C&P sub-categories in PAS remain this opportunity intact even under the Moderate scenario.

As it has been mentioned before, estimations for energy use for lighting and appliances in 2050 are rather conservative, as they follow the trends of BUENAS' BAU scenario, which does not consider energy efficiency improvements and/or respective policy interventions. In order to evaluate how the picture presented in the tables above may change if more efficient lighting and appliances are used in buildings a hypothetical scenario was constructed, which presumes 50% reduction in energy intensities for lighting and appliances in 2050 in relation to BAU (this reduction is based on the approximate difference between the results for the residential sector under BAU and Best Policy scenarios of BUENAS model). The results for meeting electric energy use needs by solar electric energy in 2050 with hypothetical efficiency scenario for lighting and appliances are presented in Table 31and Table 32.

Table 27 Meeting thermal energy use needs by solar thermal energy in 2050, Deep scenario

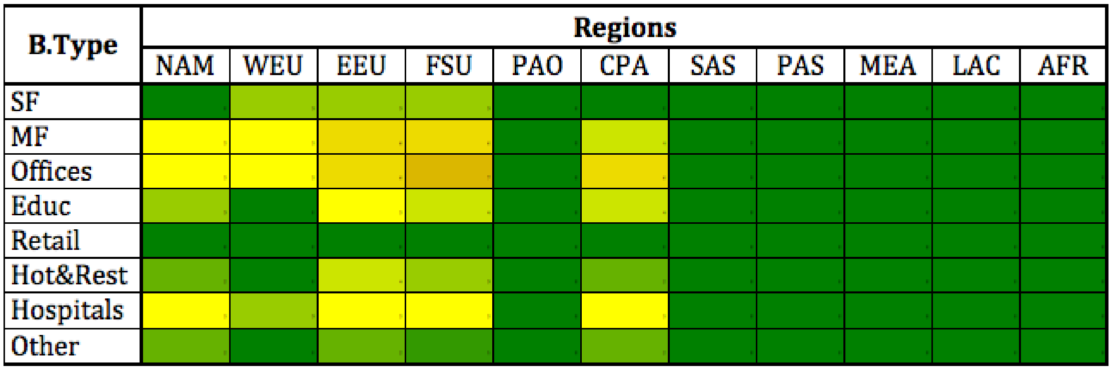



Table 28. Meeting thermal energy use needs by solar thermal energy in 2050, Moderate scenario

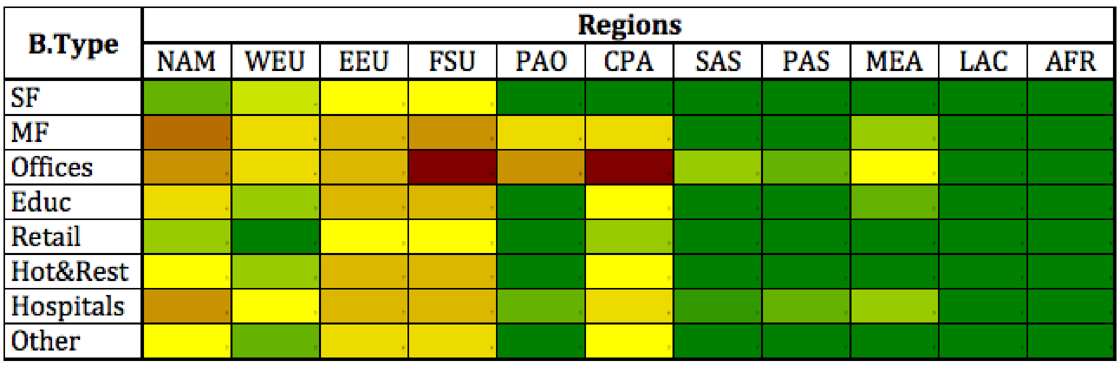



Table 29 Meeting electric energy use needs by solar electric energy in 2050, Deep scenario

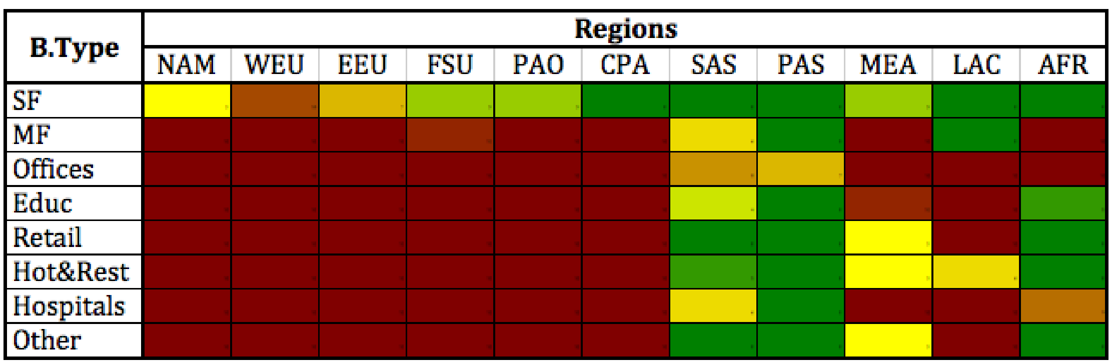
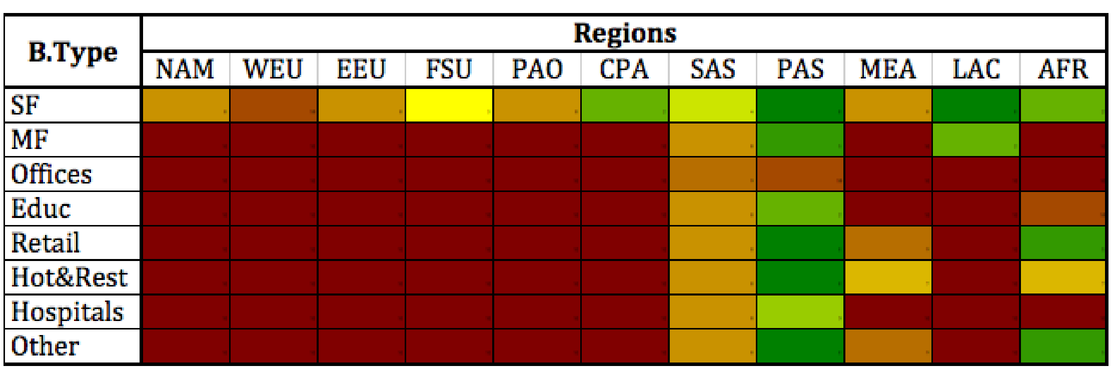



Table 30. Meeting electric energy use needs by solar electric energy in 2050, Moderate scenario




Different colors show number of months during the year 2050, in which energy use is covered by solar energy supply

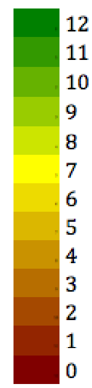


Table 31. Meeting electric energy use needs (with reductions for energy intensities for lighting and appliances) by solar electric energy in 2050, Deep scenario

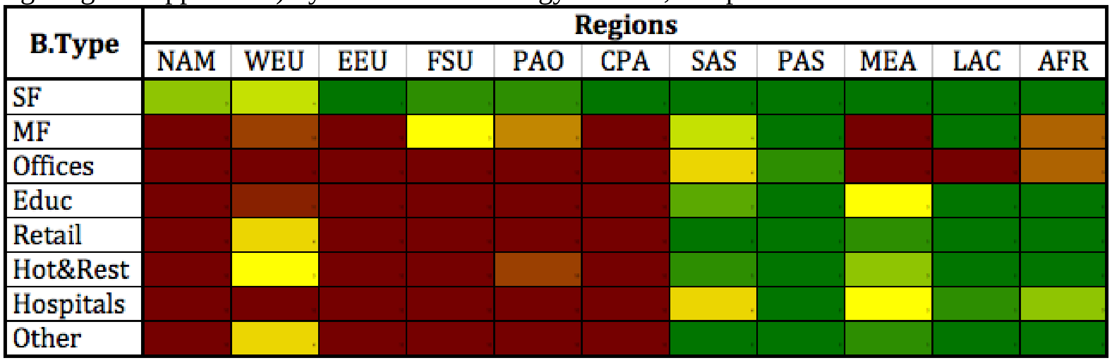
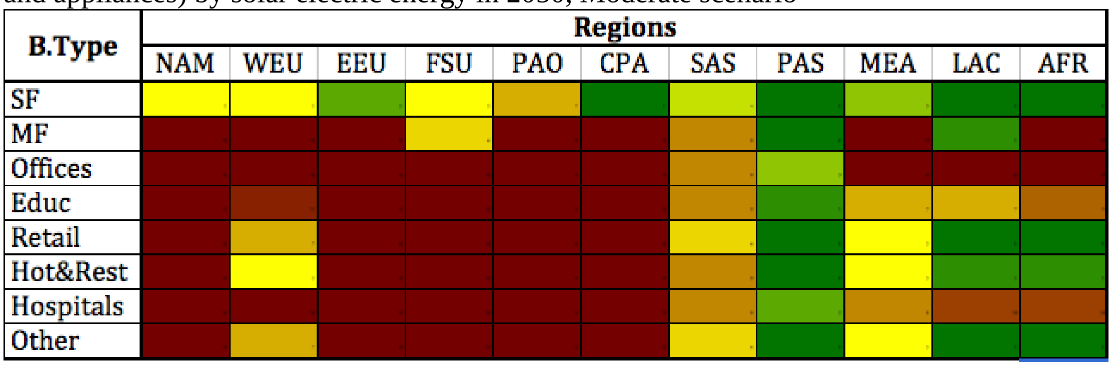
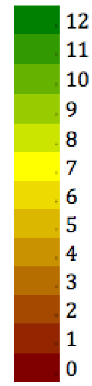



Table 32. Meeting electric energy use needs with reductions for energy intensities for lighting and appliances) by solar electric energy in 2050, Moderate scenario




Different colors show number of months during the year 2050, in which energy use is covered by solar energy supply




Comparison between Table 31 and Table 29 demonstrates that more energy efficient lighting systems and appliances increases the chances to meet all electrical needs with solar energy in a number of regions and building types under Deep scenario. It is especially noticeable in low- and medium-height building types. For example, in all the regions single-family buildings show increase is a number of months, in which total coverage of electricity use can be achieved, which brings buildings of this type even closer to net-zero energy (and in some regions even energy positive) level. Retail and other buildings, as well, as hotels & restaurants demonstrate increase in a number of months with at least zero energy balance for electrical end-uses in WEU, MEA and LAC regions.

Such a reduction in energy demand for lighting and appliances has led to improved monthly energy balances for multifamily buildings in several regions, e.g. WEU, FSU, PAO, SAS and AFR. However, these energy efficiency improvements turned to be insufficient in order to increase a number of regions with the full solar electric coverage across the months for this building type. Even lower impact can be observed when C&P sub-categories (besides the ones mentioned earlier) are studied. Although more efficient lighting and appliances generally increase the solar fraction for all building types, in commercial and public buildings it is less noticeable from the tables, as such an increase in most of the cases does not significantly change the number of months with zero or positive energy balances. The main reason is twofold: on the one hand, it is high overall electrical needs in commercial buildings even in case of 50% reduction in the energy intensities and, on the other, - limited solar electricity supply due to building geometry.

Another observation from the comparison of these two tables is that more energy efficient lighting and appliances play a more significant role in developing regions than in developed ones. This impact can be potentially increased through a combination of energy efficiency improvements with policies

Table 31 shows that under Deep scenario most of the building types in developing regions (from SAS to AFR) moved closer to the green end of the spectrum in comparison to the situation with BAU energy intensities for lighting and appliances (Table 29), while in most of developed regions the situation has barely changed.

Results for Moderate scenario (Table 32) show notably lower potential for covering electrical needs with solar energy than in case of Deep scenario. In comparison to Table 30 the picture has not changed significantly in terms of increasing a number of cases (i.e. months plus building types) with full solar electrical coverage. It demonstrates the importance of the holistic approach: energy efficient lighting and appliances should be combined with the best-practice solution for the building shell and related technologies (e.g. space cooling).

For illustrating the outcomes of the comparative analysis between Deep and Moderate scenarios, the results of the building energy use and solar energy supply for every month are presented in charts for each region.

**Figure 45 - Figure 47** compare results for thermal energy use and solar thermal energy production under the Deep and Moderate scenarios for three building types: single-family, multifamily and commercial & public buildings, while **Figure 48 - Figure 50** show the same type of the results for electric energy use and solar electricity.

The figures clearly show the importance of energy efficiency for net-zero energy buildings. Thermal and electric energy uses under Moderate scenario are much higher than those under the Deep one in all regions and building types. Therefore, it is much more difficult to satisfy these energy needs only with solar energy. It is particularly critical in developed regions, which have relatively low availability of solar resources and higher energy requirements for space heating. **Figure 45 - Figure 47** demonstrate that in case of the Moderate scenario the need for the back-up space heating systems is much larger as much higher energy demand has to be satisfied during winter months. Therefore, larger amount of fossil fuel energy is likely to be consumed and greater amount of GHG emissions is to be produced (unless the supplementary heating uses other renewable energy sources). In developing regions larger thermal energy use might mean that less thermal energy is available, for example, for solar thermal cooling (if this option is considered). Higher thermal and electric energy use under the Moderate scenario may also limit the opportunity for downsizing of the solar systems and, therefore, reducing the related costs.

The major difference between scenarios for electric energy use can be seen in the regions with cooling-dominated climates (as energy intensities for lighting and appliances are assumed to be the same under both scenarios) and during summer months. For example, in SAS and MEA under the Deep scenario electric energy use in single-family buildings can be satisfied by solar energy even during the peak-cooling months (except for July in MEA), however, under the

Moderate scenario it becomes impossible during 3-4 months due to higher cooling demand. A common trend can be seen in all building types and regions: lower energy efficiency of buildings increases difficulty in achieving net-zero energy goal and/or may aggravate the problem of oversizing of the solar systems.

The results of the comparative analysis presented above have clearly demonstrated that energy consumption for appliances and lighting play a very important role on the way towards net zero energy buildings supplied by solar energy. Increase in the energy efficiency for these end-uses can significantly increase solar fraction in most of the regions and building types. It also boosts up the chances of achieving net-zero energy (or even positive energy) status for low-rise building types (e.g. single-family buildings and in some cases retail buildings).

Developing regions have demonstrated higher sensitivity towards improvements in lighting and appliances energy performance, as they usually have lower energy demand for these end-uses than developed countries. It increases the importance of strict product standards and lighting regulations in these regions in order to realize the potential for energy savings.

In more details the impact of variations in energy intensities for lighting and appliances on the overall electric energy balance and potential for solar coverage are discussed in Section VIII.7, where respective results for the sensitivity analysis are presented.

The key conclusion of this section is that energy efficiency of all systems, related to both building shell and plug loads, should be maximized in NZEBs in order to increase the chances of covering all energy needs throughout the year, as well as to reduce the size of building-integrated renewable energy systems, which will allow lowering the investment costs and the amount of embedded energy related to the production of the technology.

Therefore, this dissertation strongly advocates for including the requirement for high level of energy efficiency into the definition of NZEBs.

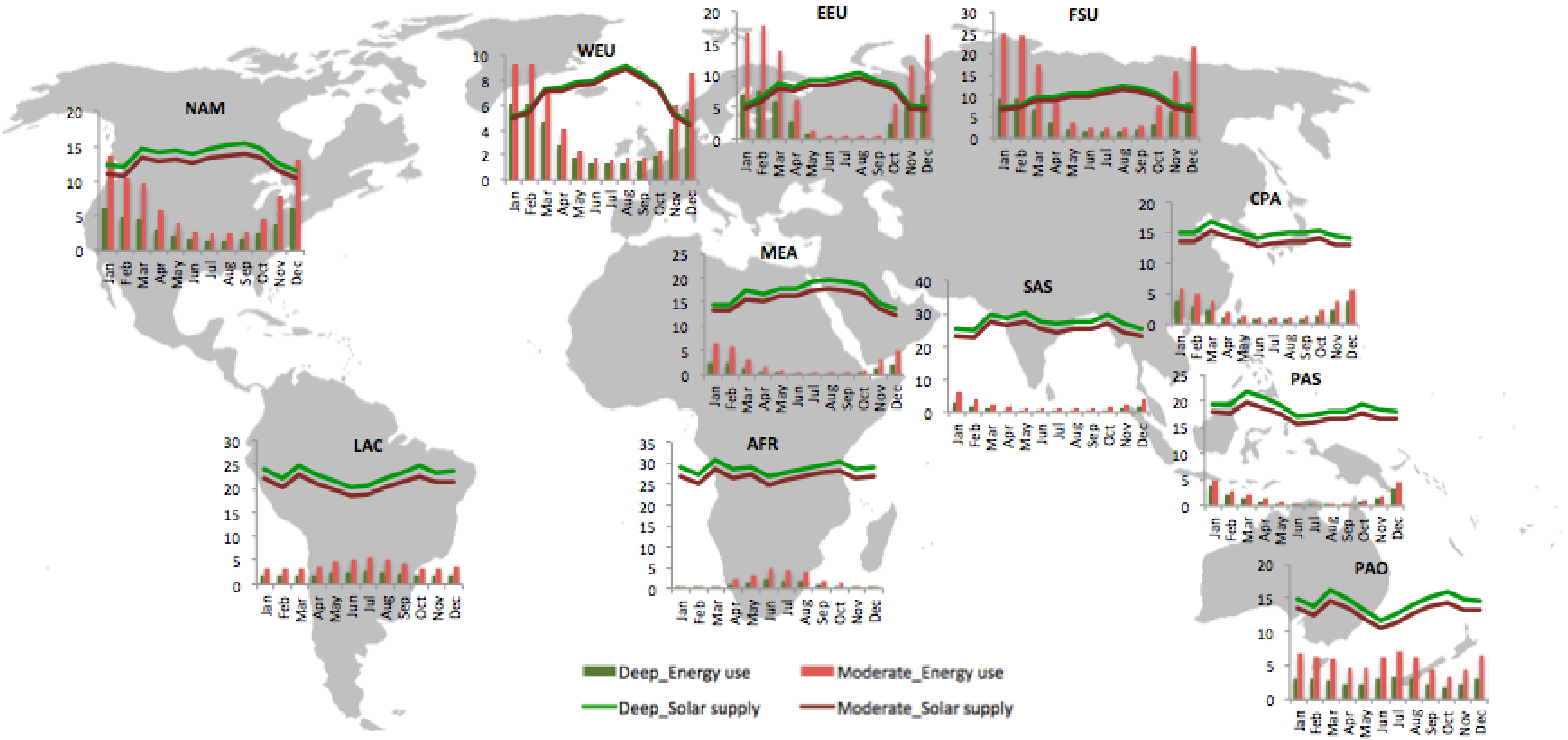



Figure 45. Thermal energy use vs solar thermal energy production for single-family buildings in 2050, kWh/m2 of floor area, Deep vs Moderate scenarios

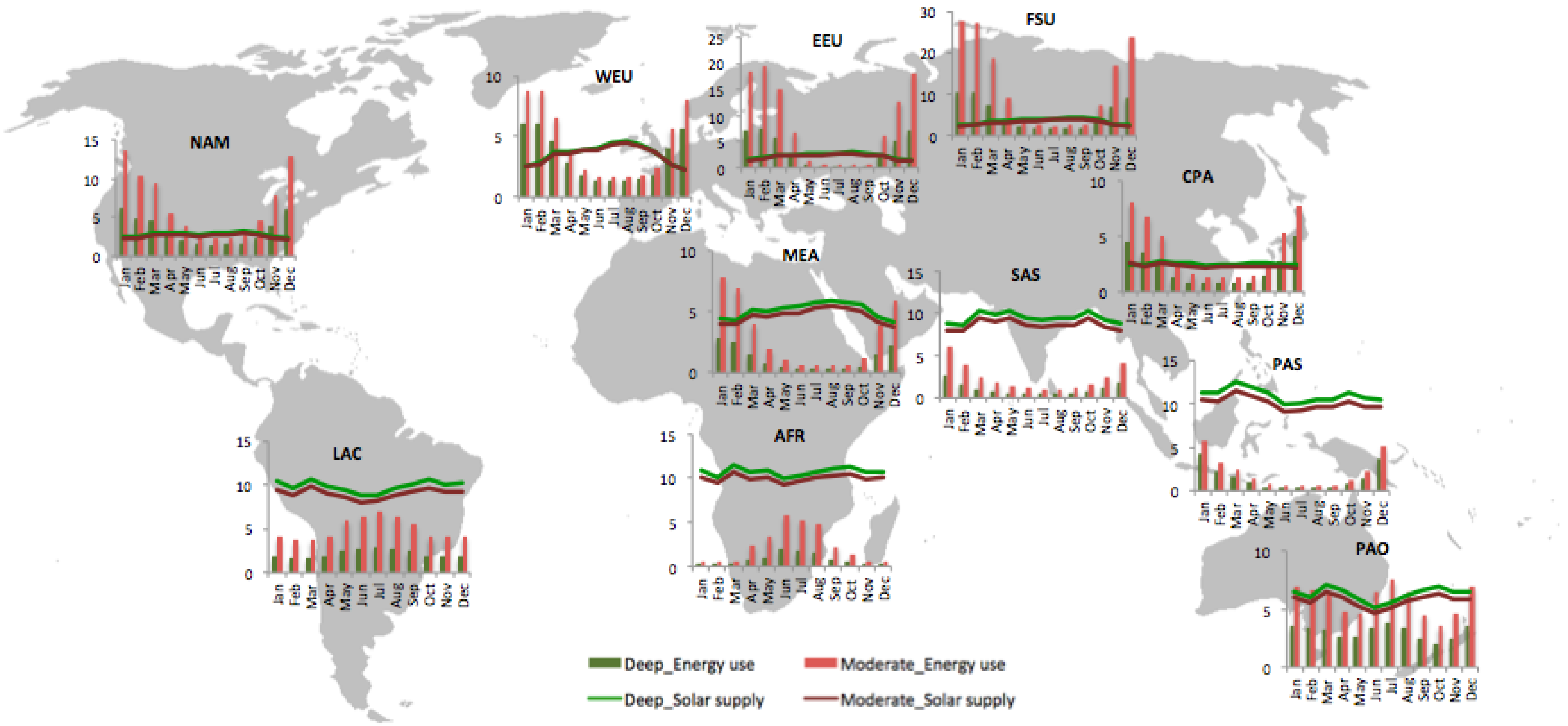



Figure 46. Thermal energy use vs solar thermal energy production for multifamily buildings in 2050, kWh/m2 of floor area, Deep vs Moderate scenarios

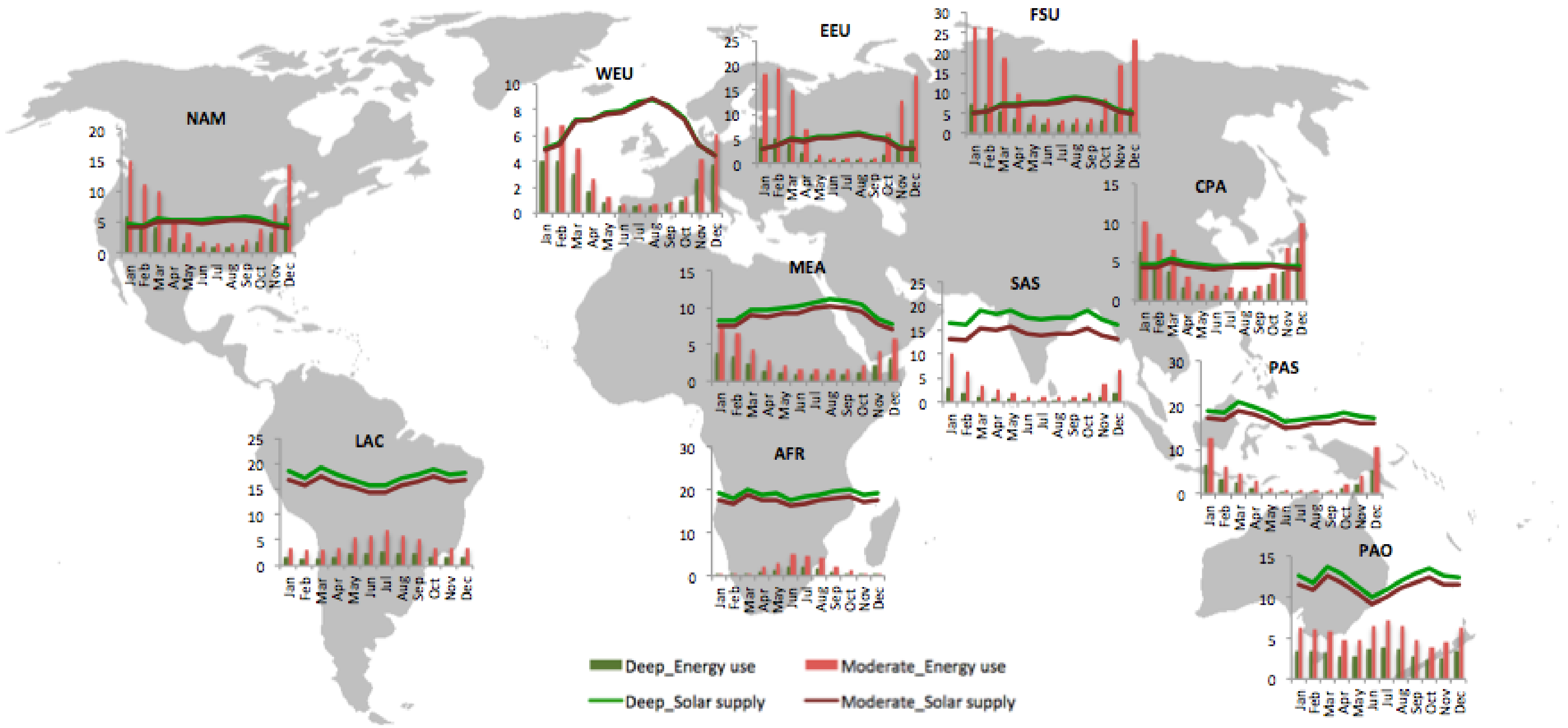



Figure 47. Thermal energy use vs solar thermal energy production for C&P buildings in 2050, kWh/m2 of floor area, Deep vs Moderate scenarios

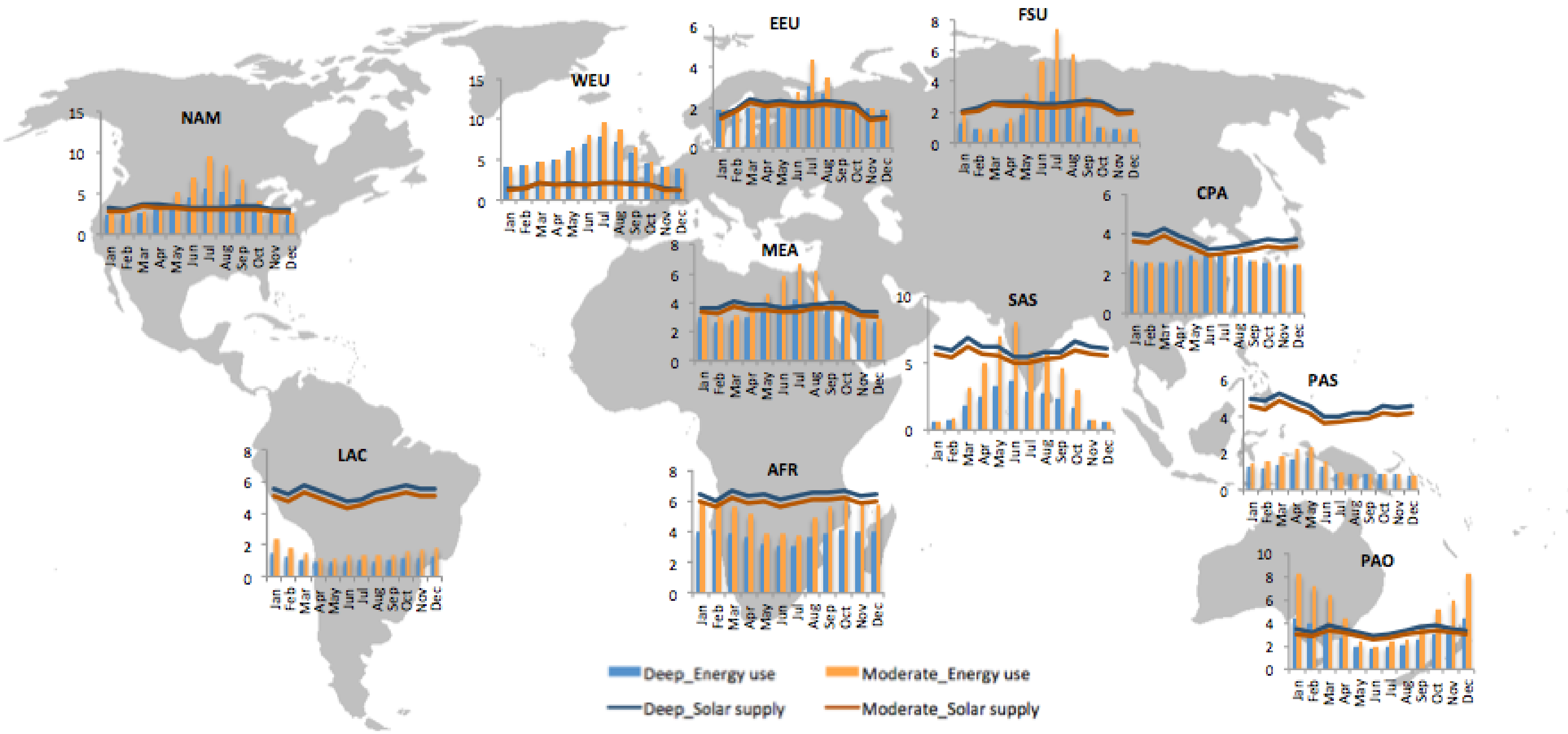



Figure 48. Electric energy use vs solar electric energy production for single-family buildings in 2050, kWh/m2 of floor area, Deep vs Moderate scenarios

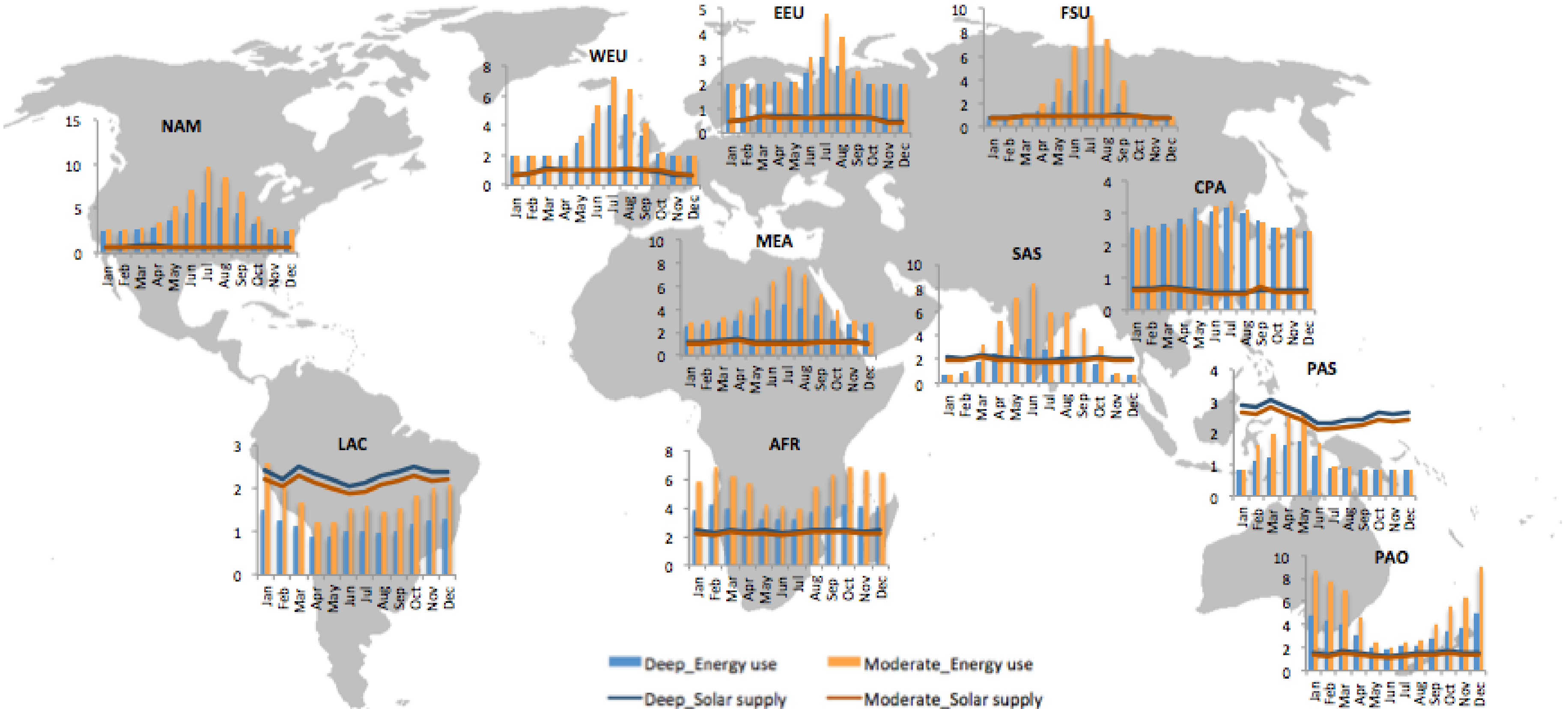



Figure 49. Electric energy use vs solar electric energy production for multifamily buildings in 2050, kWh/m2 of floor area, Deep vs Moderate scenarios

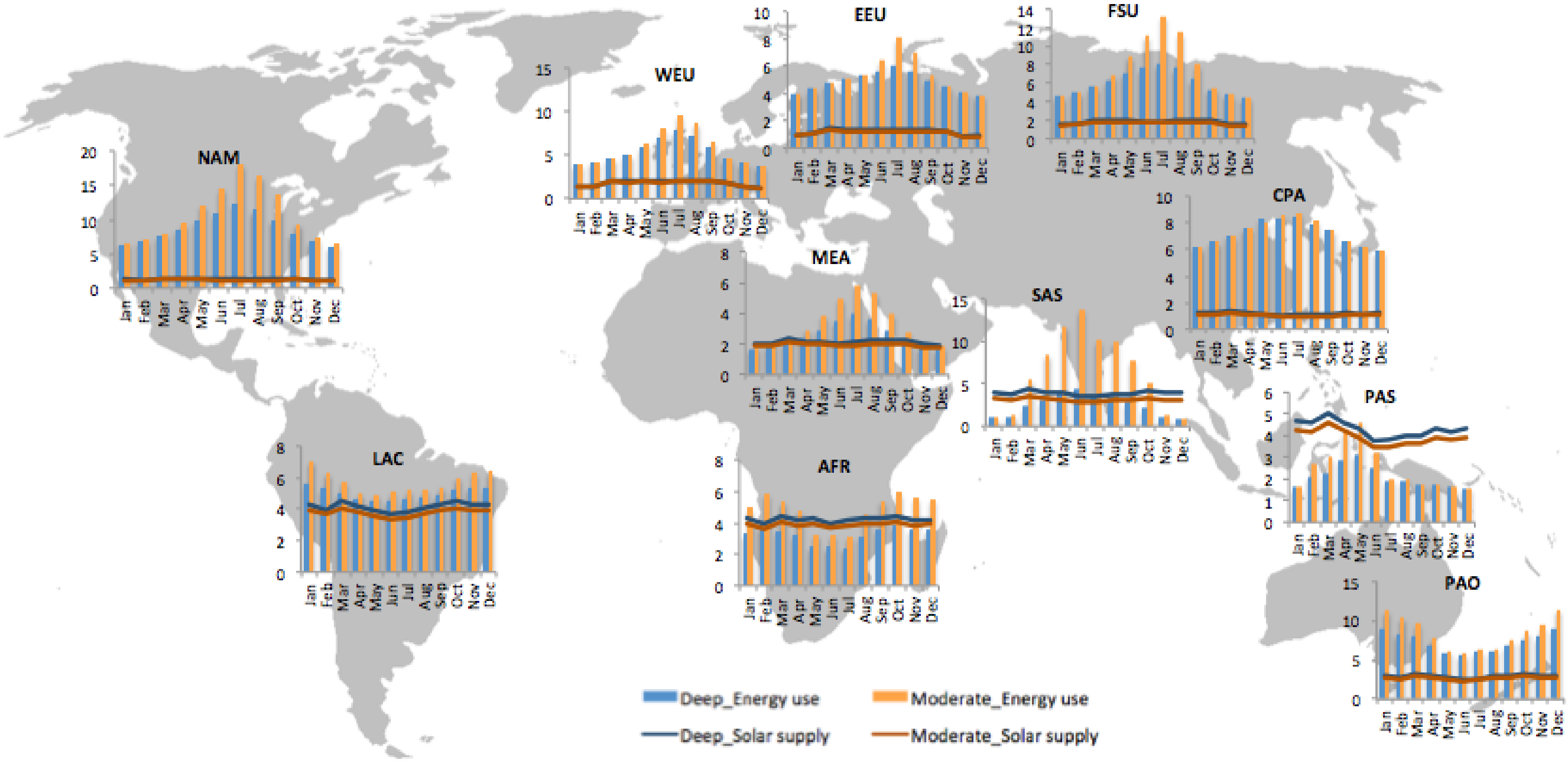



Figure 50. Electric energy use vs solar electric energy production for C&P buildings in 2050, kWh/m2 of floor area, Deep vs Moderate scenarios

## VIII.4 Moderate climates offer higher potential for NZEBs

**KEY MESSAGE**:
Buildings located in the areas with moderate climate zones have higher chances to achieve NZE goal (on a monthly scale) (due to modest heating and/or cooling loads) than those situated in the zones with high demand for heating and/or cooling

On one hand, climate conditions influence the amount of energy consumed in buildings and determine the priority purposes, for which energy is used in buildings (i.e. end-uses). On the other hand, climate conditions have a direct impact on the performance of the solar technologies (for example, different level of solar radiation, ambient temperature, wind speed, etc.). Therefore, it is important to consider climatic factors, when analysis the potential for net-zero energy buildings.

This section explores the influence of climate conditions on the trends in the energy balance and potential for achieving net-zero energy goal with solar energy. For this purpose several regions and a number of climate zones were selected and the results for each of them are presented separately for thermal and electric energy in **Figure 51-Figure 54**.

**Figure 51** - **Figure 52** present the results for NAM, WEU, SAS and CPA. **Figure 51** shows that cooling-dominated climate (Only Cooling, High demand) has the highest solar thermal output in all four analyzed regions. At the same time it has the lowest (or no) heating demand and, therefore, demonstrates the opportunity not only cover all thermal energy needs, but also produce a significant amount of excessive heat.

The climate zone, which presumes both moderate heating and moderate cooling demand has a slightly lower solar thermal potential among all four regions, but notably higher heating needs. Despite this fact in all the regions solar thermal energy supply is estimated to be sufficient to cover energy use for space and water heating throughout the year. The problem of overproducing solar heat occurs only during summer months.

Different picture is seen for the heating-dominated climate zone (Only Heating, High demand). Here in all regions, except for SAS, thermal energt use cannot be covered by produced solar heat to full extent at least during 3 coldest months of the year. It is explained by both lower solar thermal output and higher heating energy demand.

The last among selected climate zone, which combines the need for heating, cooling and dehumidification, shows similar results to the heating-dominated one. The level of solar thermal output is a bit higher that in the “Only Heating” case for all the regions, except for China. Heating demand is also significant, however, there are fewer months, when heating is needed than in the heating-dominated climate.

Solar electric potential looks more uniform among the climate zones, however, in absolute number variations among climate zones follow similar trends, as the ones for the solar thermal energy described above (but in smaller absolute numbers). Electric energy use, on the contrary, in absolute values is significantly higher than thermal energy use. It can mostly be explained by business-as-usual energy intensities for lighting and appliances. In climate zones with high and moderate cooling demand (“Only Cooling (High demand)”, “Heating (Mod d) & Cooling (Mod d) and in some regions, like SAS, “Heating & Cooling & Dehumidification”), specific energy consumption for space cooling is also substantial. These high values for specific energy consumption and limited solar electricity production lead to the situation, in which in most of the regions and climate zones electrical energy use cannot be covered by solar energy throughout the year.  The exceptions are two climate zones in SAS, where cooling demand is not very high or cooling is not required (Only Heating).

**Figure 53** and **Figure 54** present the results respectively for thermal and electric energy use and solar energy generation for different climate zones in other regions, namely: PAO, FSU, AFR, LAC. The common trend among these regions is that in the climates, where there is moderate or high demand for heating it is unlikely that 100% of thermal energy can be covered by solar energy generation in all months. The exception is Latin America, where even in case of moderate heating demand excess solar heat can be produced in all months. Sun-Saharan Africa also shows very high potential for solar thermal energy production. As the thermal energy demand in this region is quite low in all presented zones, large amount of excessive heat will be produced in all months. As in both LAC and AFR regions most of the electricity demand can be covered by solar in the presented climate zones, it is likely that the solar systems should be downsized or shaded during summer months and, as an option, excess solar heat can be used for space cooling.

Therefore, the results discussed above show that climate conditions play a very important role on the way to the net-zero energy future of buildings. In the cooling-dominated climates the main emphasis should be made on renewable electricity supply. As the results show solar electricity alone might not be a sufficient energy source in a number of regions (at least in certain building types).

If the electrical end-uses are the priority, one of the possible solutions can be the installation of an unglazed solar PV/T system on a larger portion of the roof and an efficient solar thermal collector on the remaining area for covering energy needs for water heating. The unglazed PV/T has a higher electrical efficiency due to reduced optical losses and the operating temperature of the system can be kept relatively low, as PV modules are cooled by the fluid, which is preheated and stored in the thermal storage tank inside the building (Tripanagnostopoulos 2013). That is likely to be a sufficient solution for developing countries with abundance of the sunshine and relatively low specific electricity consumption.

For the regions and climate zones, where both cooling and heating play a substantial role among building energy uses, PV/T system (or unglazed PV/T + solar thermal collector) can be combined a solar electricity powered geothermal pump. During cold period of the year the heat pump would supply a large portion of the space heating, which can be also boosted by the fluid preheated by the PV/T system. During the warm part of the year cooling can be covered by solar-powered electrical fans (up to 33°C) or air-conditioning supplied by the heat pump (above 33°C). If the solar thermal output is sufficient, solar cooling can be an alternative solution.

The results presented in this section have clearly shown that climate has a very high impact on energy balance and potential to get to net-zero in buildings. Climate zones, which have high peak demands for space heating or cooling, or both, may require imply difficulties for a number of building types to cover all energy needs with solar energy during these months, while areas with more moderate climate have better chances for accomplishing significant solar fractions.

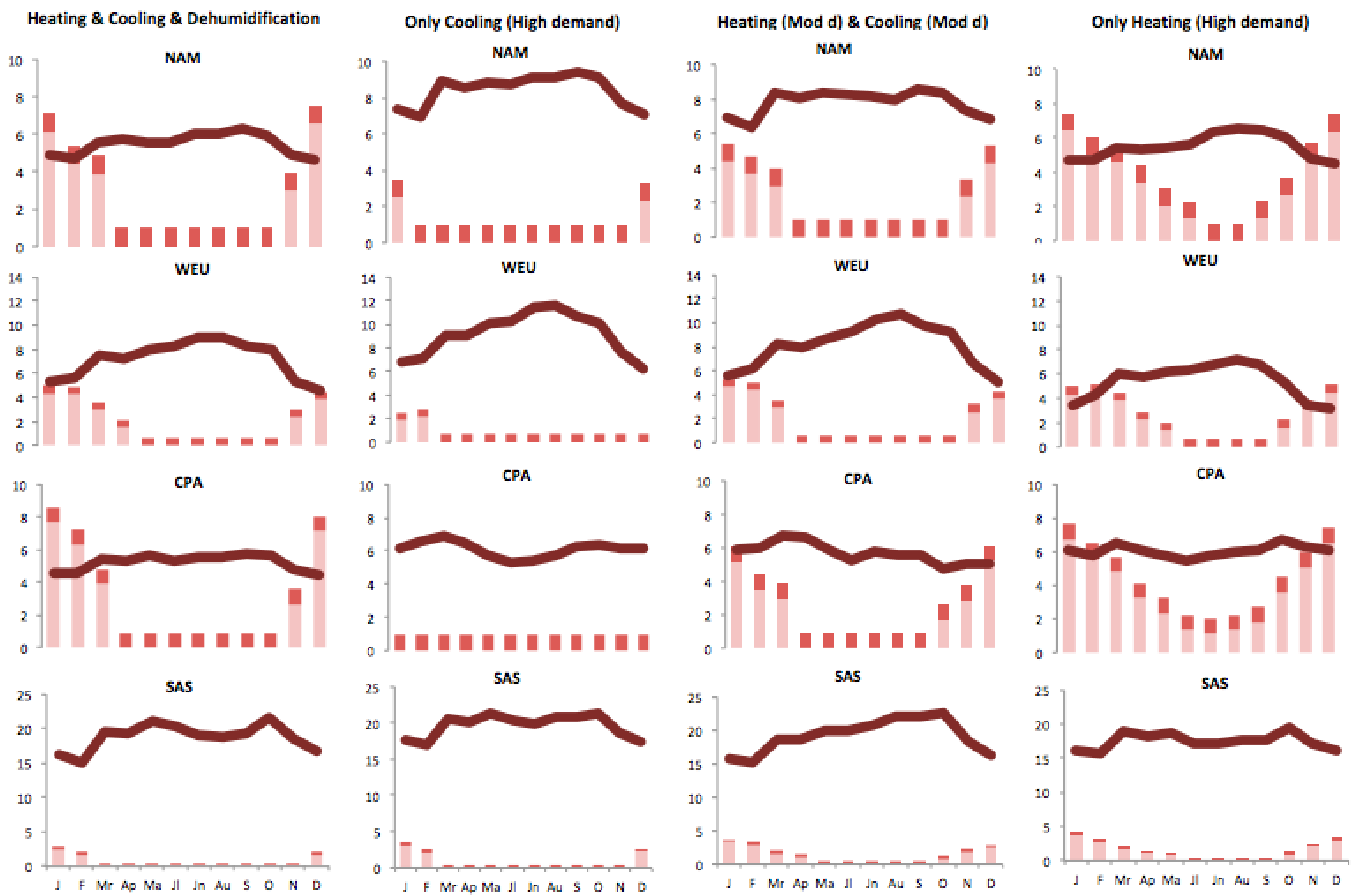



Figure 51. Thermal energy use vs solar thermal energy production in 2050 for selected climate zones and regions, kWh/m2 of floor area, Deep scenario

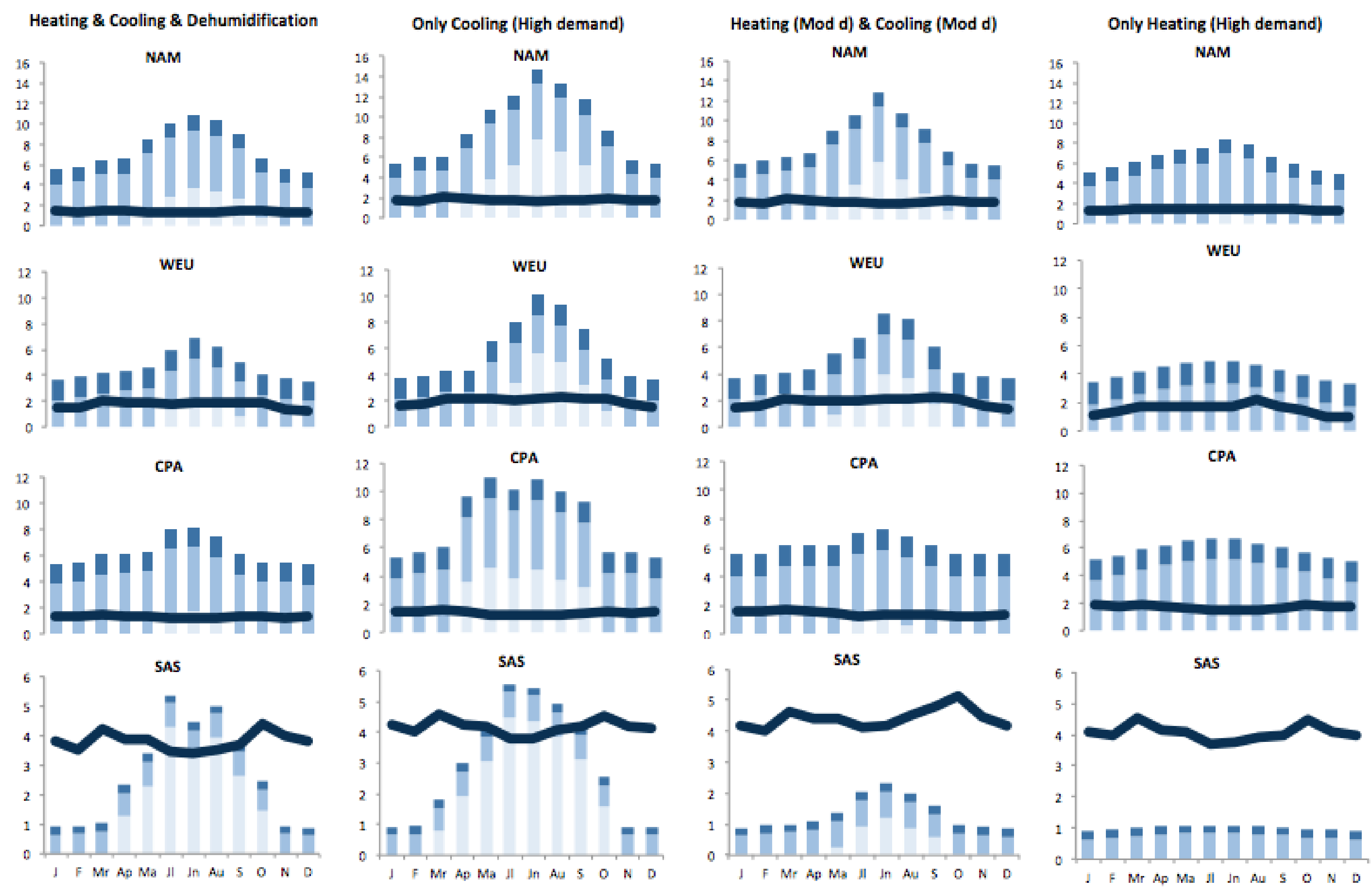



Figure 52. Electric energy use vs solar electric energy production in 2050 for selected climate zones and regions, kWh/m2 of floor area, Deep scenario

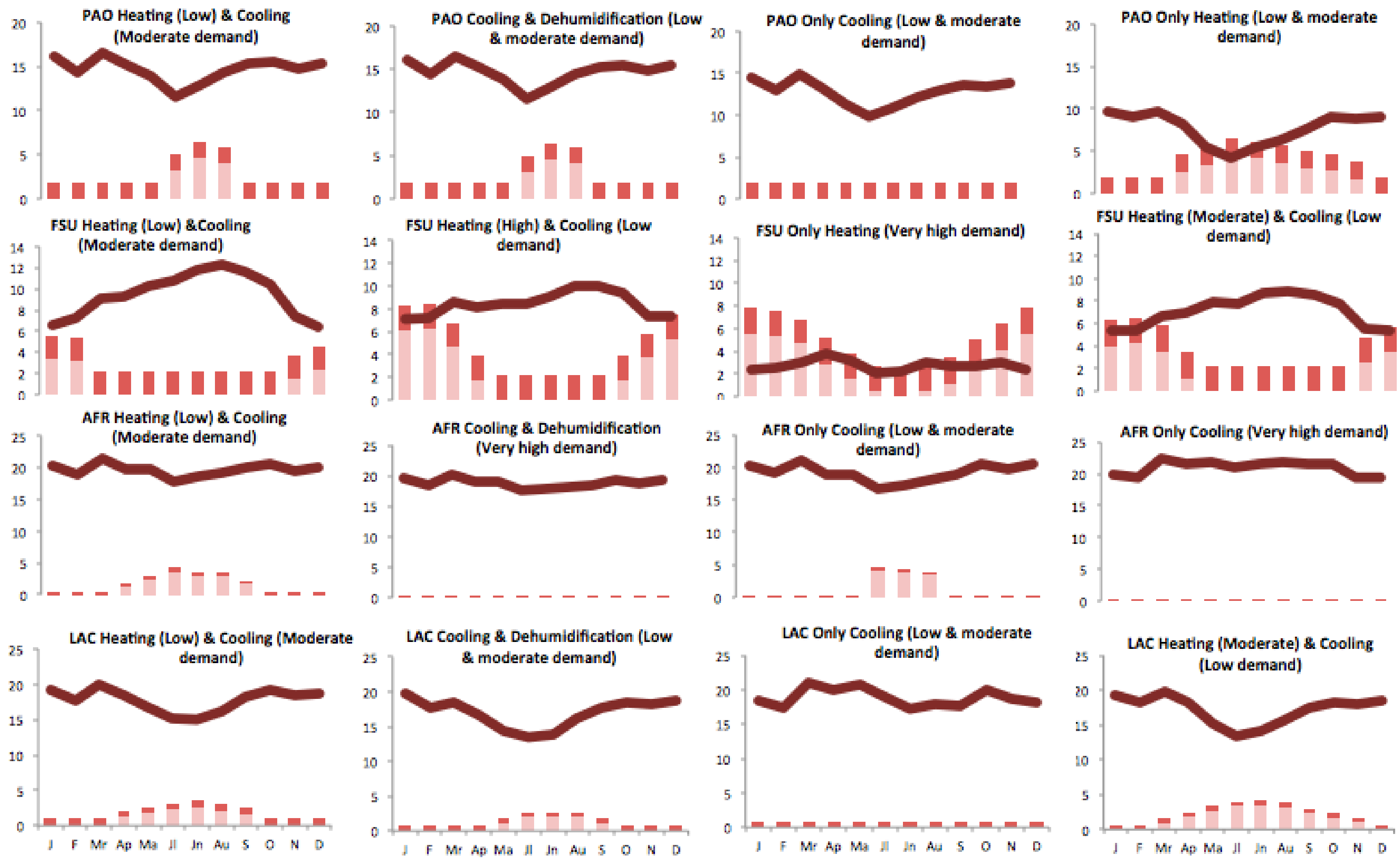


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Figure 53. Thermal energy use vs solar thermal energy production in 2050 for selected climate zones and regions, kWh/m2 of floor area, Deep scenario

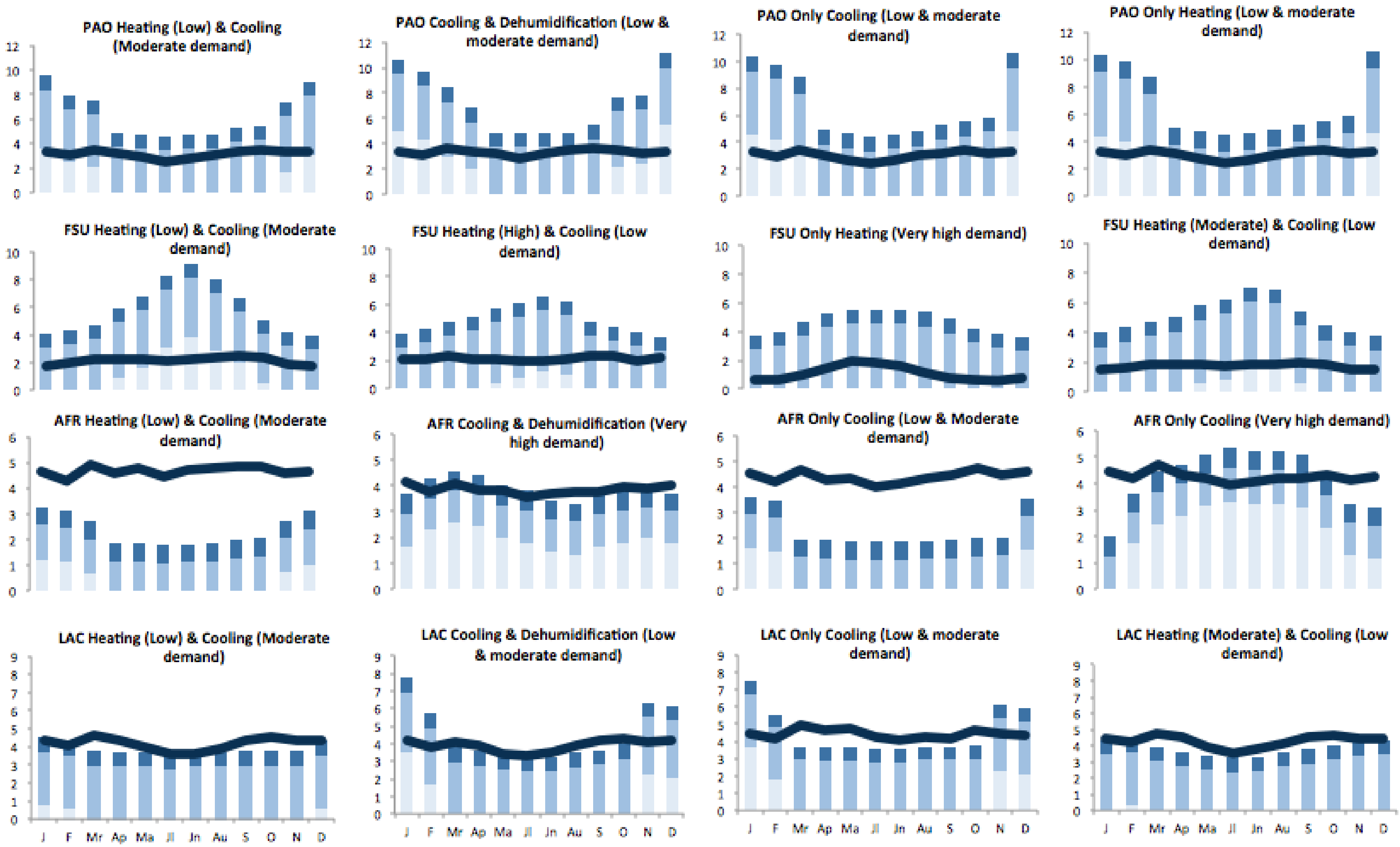


Figure 54. Electric energy use vs solar electric energy production in 2050 for selected climate zones and regions, kWh/m2 of floor area, Deep scenario

## VIII.5 Realisation of solar potential in buildings in developing countries allows for their ‘leapfrogging’ to a more sustainable path

**KEY MESSAGE**:
Buildings in developing countries demonstrate an enormous potential for on-site solar energy production. Should this potential be realized, building sectors in these regions could have sustainable, low-carbon and even energy positive future.

As it was demonstrated in **Figure 45 - Figure 50** developing regions have notably higher solar energy potential than developed ones. At the same time if ambitious energy efficiency improvements are implemented in the building sectors of these regions, building energy demand can be significantly reduced without compromising thermal comfort. Realization of renewable energy potential together with large-scale energy efficiency interventions increases the chances for the developing countries to ‘leapfrog’ towards low-energy and low-carbon buildings without creating additional harmful environmental effects.

Figure 55 - Figure 56 demonstrate electric energy use versus potential solar energy production in kWh per square meter of the floor area for residential and commercial buildings, as well as the total floor area, in four developing regions. The figures present the results for July and January between 2005 and 2050 with five-year interval.

It can be seen in Figure 55 that floor area in both single-family and multifamily buildings is rapidly growing by 2050 in all analyzed region. Despite this dramatic increase and the assumption for the improvement in the level of life in developing countries (which among others is reflected in the increasing energy intensities for appliances), the total electric energy intensities are decreasing by 2050, mostly due to enhanced energy performance of buildings and lower energy demand for space cooling achieved through energy efficiency improvements. In single-family buildings in all presented regions this reduced electricity use can be covered by potentially produced solar electricity by 2050 to a large extent (the only exception is July in MEA region). Single-family buildings in LAC, PAS and AFR regions may also provide an opportunity for the export of the excess solar energy produced on site. In other words, under the assumptions accepted in the BISE model single-family buildings in these regions show a considerable potential to become energy positive or ‘energy-plus’ buildings.

In LAC and PAS regions building needs for electricity can also be met in multifamily buildings through solar generation, while in AFR and especially in MEA region, certain back-up source of electricity would be needed in this building type. One of the key reasons for such difference energy intensities for appliances, which are higher in AFR and MEA regions than in LAC and PAS. If more energy efficient appliances are used in these regions, the potential for net zero energy building will become even higher.

As for commercial buildings, which are in this section represented by office and educational buildings, potential to cover electricity demand in buildings by building-integrated solar electricity in these building types is notably lower than in residential buildings (see Figure 56).

The reduction in energy intensities in these building types over the time is less obvious than in residential buildings, especially in LAC and MEA regions, due to a large share of lighting in the commercial buildings and high lighting energy intensities, coming from business-as-usual scenario of the BUENAS model. As this scenario does not assume a significant improvement in the lighting energy efficiency, simple replacement of the light bulbs with more efficient types and introduction of other common energy saving strategies for lighting widely available for commercial buildings, can significantly reduce total electrical energy intensities in commercial buildings.

While electrical energy use intensities are quite similar in educational and office buildings, the amount of estimated solar electricity, which can be produced in these two different building types is quite different. Educational buildings demonstrate higher solar electricity potential per square meter of the floor area than office and even multifamily buildings mostly due to lower height of typical educational buildings and, therefore, larger roof-to-floor ratio. As BISE model's results show in PAS and AFR regions solar electricity is estimated to be sufficient to cover electrical energy needs in educational buildings by 2050 (an even several years earlier). Lower (than in LAC & MEA) energy intensities for lighting in these two regions is one of the reasons for this.

Taking into account the discussion presented above and the fact that thermal energy needs can be covered by solar energy in most analyzed building types and regions (see Figure 57 and Figure 58), it can be concluded that residential buildings (especially single-family), as well as some commercial building sub-categories (for example, educational buildings) in most of the presented regions have a very good potential for achieving net-zero energy goal mostly with on-site generated solar energy supply. Only office buildings from the selected building types have quite significant need for the auxiliary energy sources besides solar energy produced on-site for covering both electric and thermal energy needs.

As presented in Figure 57, single-family and educational buildings in developing regions are likely to generate the amount of solar heat, much higher than thermal energy needs. Therefore, unglazed PV/T systems with maximized electric efficiency might be more advantageous for these building types located in hot and sunny climates, which would allow for increasing the amount of solar electricity. Amount of the solar heat produced by the thermal part of the PV/T system would be sufficient to provide hot water throughout the year. In case there is still solar electricity available after satisfying building energy needs, the buildings can supply the extra electricity into the grid or storing it in the storage facilities.

Results presented in this section demonstrate that solar 'leapfrogging' is possible in a number of developing regions by 2050. Solar energy produced on building site can help significantly reduce energy need for fossil fuels and in a number of cases cover building energy demand.

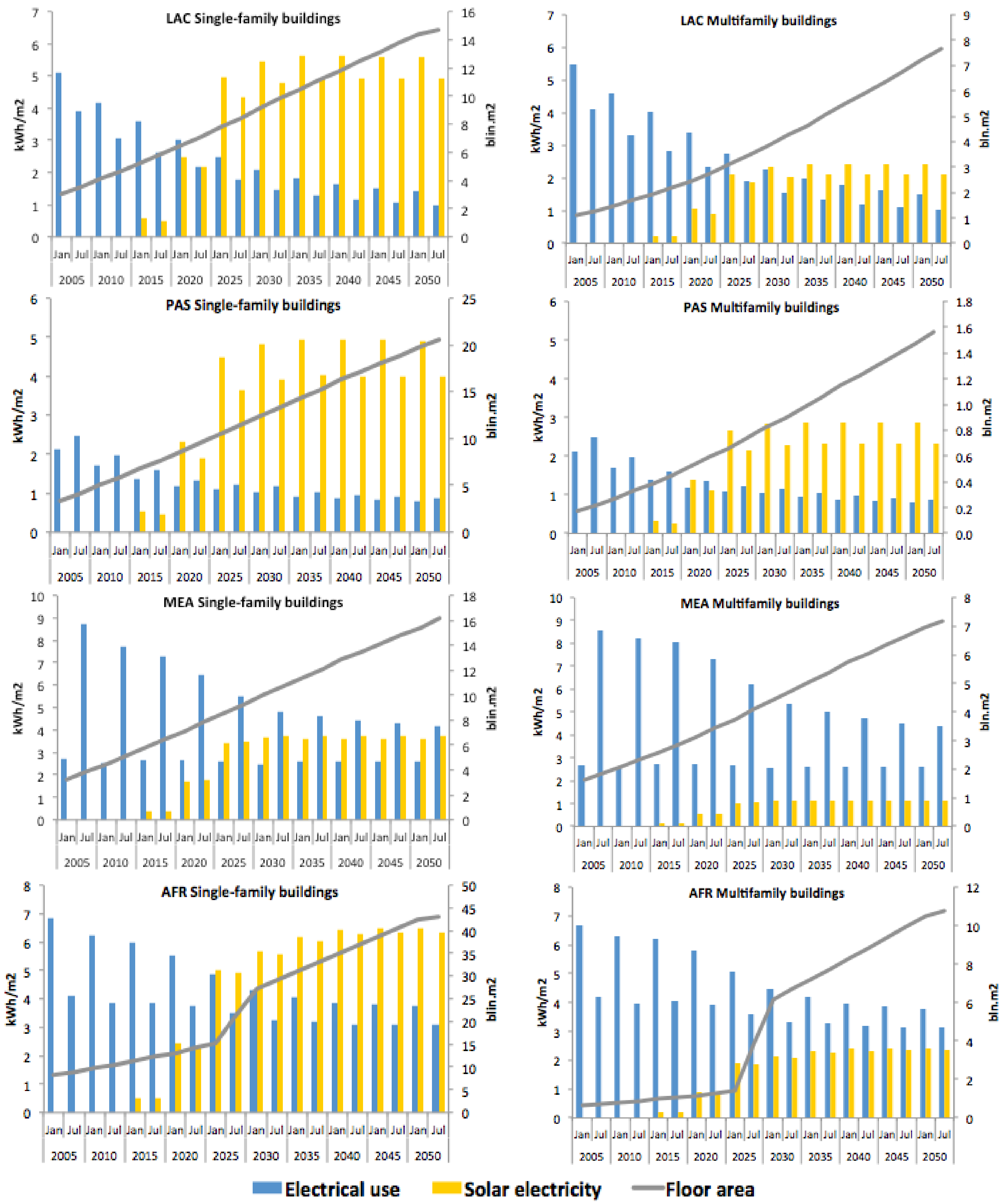



Figure 55. Electrical energy use & solar electricity per m$^2$ of the floor area in residential buildings for January and July for selected years and four developing regions. Total floor area is presented by year.

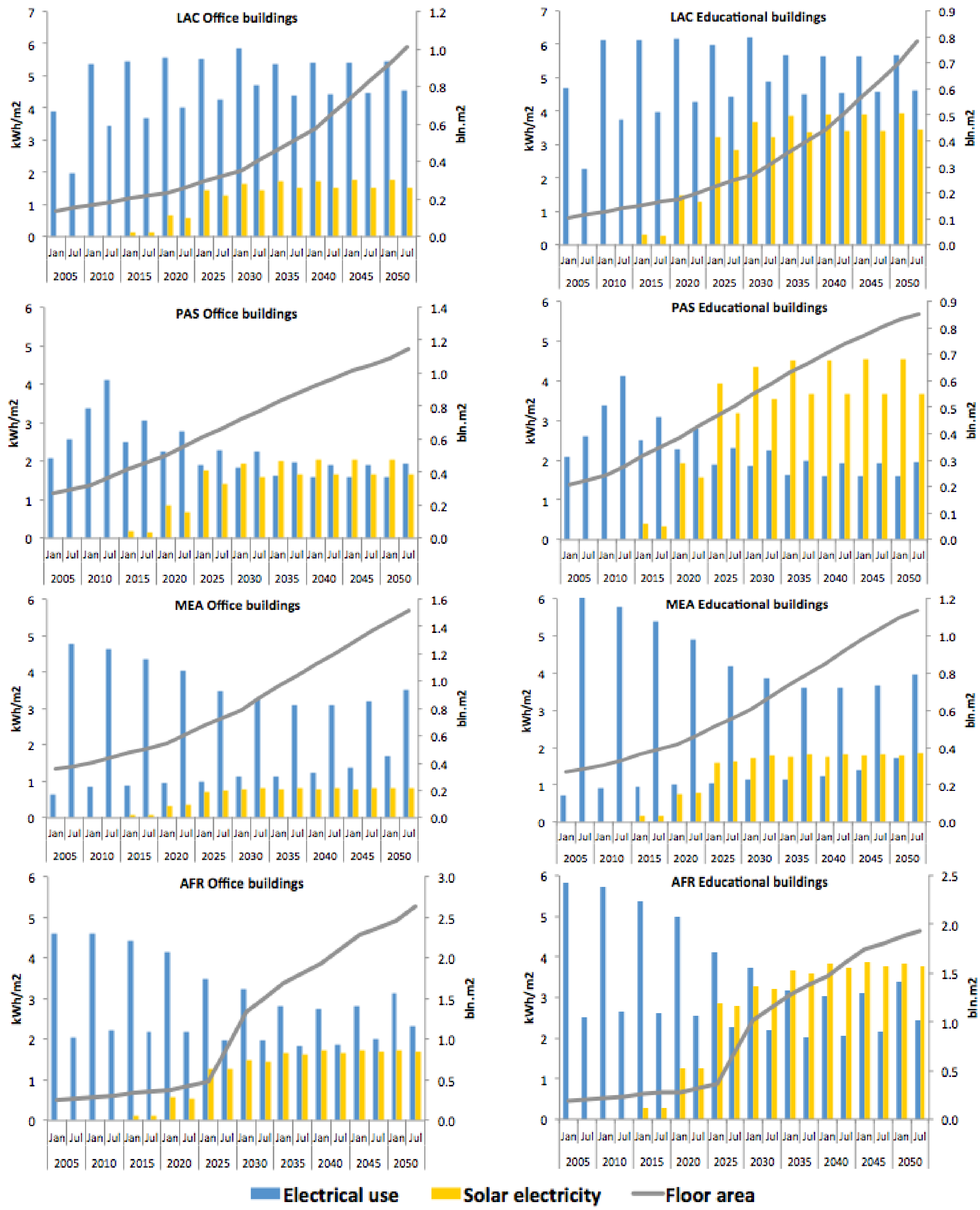



Figure 56 Electrical energy use & solar electricity per m$^2$ of the floor area in office & educational buildings for January and July for selected years and four developing regions. Total floor area is presented by year.

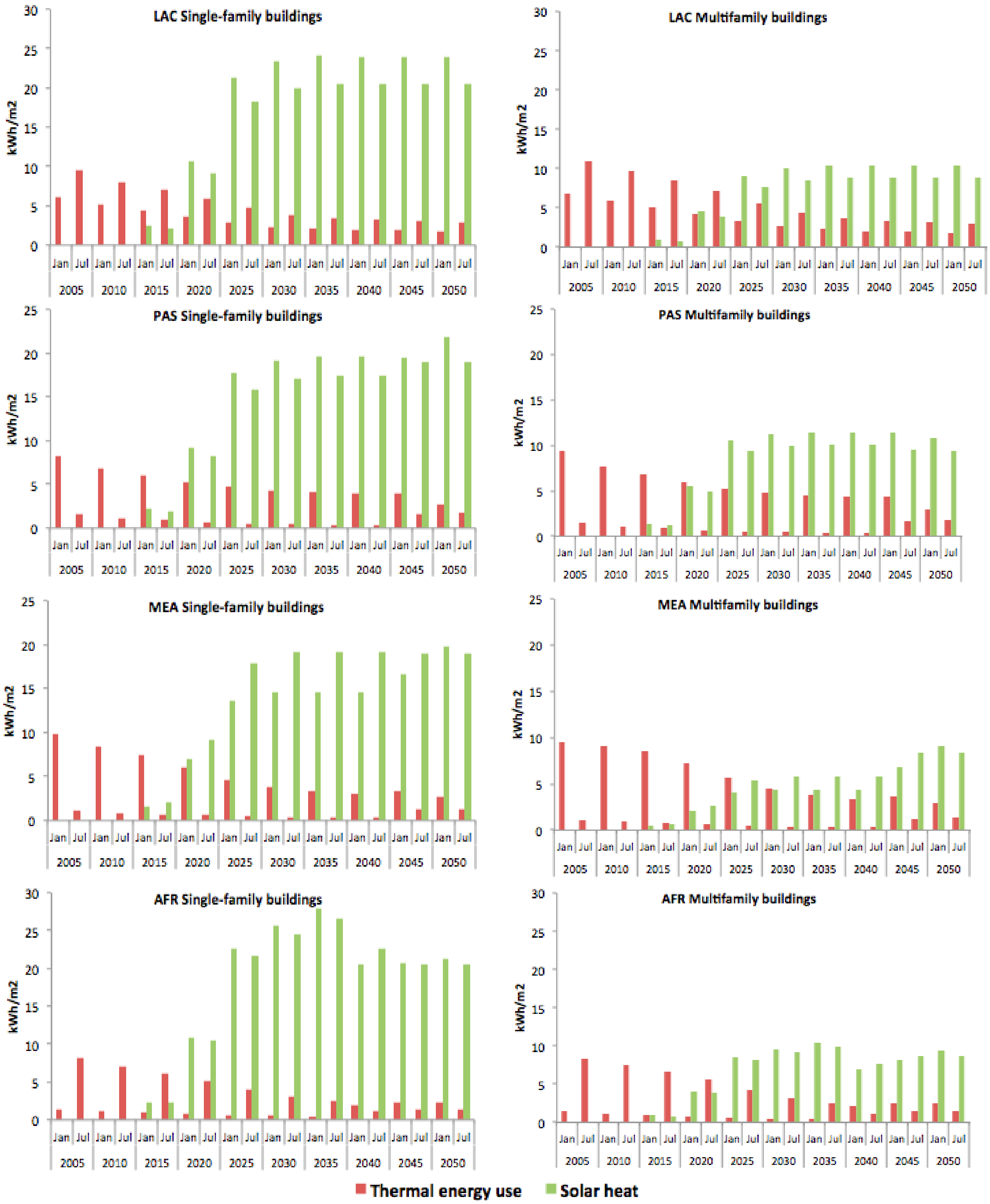



Figure 57. Thermal energy use & solar heat per $m^2$ of the floor area in residential buildings for January and July for selected years and four developing regions


Figure 58. Thermal energy use & solar heat per m$^2$ of the floor area in office & educational buildings for January and July for selected years and four developing regions

## VIII.6 Short-term energy storage can increase potential for NZEBs

**KEY MESSAGE**:
Short-term (several days) storage for solar energy can help to increase the potential for achieving NZE balance in certain building types

The aim of this section is to discuss the need for the storage of solar energy in buildings based on the results of BISE model. There are different types of technologies for storing energy for different periods of time: short and diurnal (day/night) or long and seasonal (summer/winter) (Stritih et al. 2013). Although seasonal storage may offer a greater potential for covering energy needs during the time when the availability of solar energy is more limited, it is more technologically challenging than short-term storage, requires large storage volumes, has greater risks of heat losses and higher investment requirements (Xu, Wang, and Li 2013).

Different storage technologies are discussed in the academic literature. For example, Xu, Wang, and Li (2013) focus on the seasonal storage and review three available relevant technologies. Parameshwaran et al. (2012) and Kousksou et al. (2014) present reviews of thermal energy technologies applicable in buildings, including the discussion on the storage for solar energy. Stritih et al. (2013) provide an overview of thermal energy storage concepts and technologies used in solar applications around the world with the focus on two countries: Turkey and Slovenia. It is not the purpose of this dissertation to discuss various storage technologies in detail and/or suggest optimal solutions for the buildings, as it would be hard to do on the global scale and goes beyond the scope of this dissertation.

As it was noted earlier, BISE model does not consider long-term, seasonal storage technologies, as these technologies are not yet widely used and require rather high investments. However, as the results for energy use and solar energy production in BISE model are analyzed on the monthly basis, certain short-term (within a month) storage is assumed. In order to assess the necessity of the diurnal storage in different regions and building types daily results for January 2050 were analyzed for selected regions and presented in Figure 59 - Figure 62.

As the calculation mechanism incorporated into BISE model presumes calculation with hourly data for every day of the year these data were aggregated for every day of January separately for solar thermal and solar electric energy output.

Energy use results for different end-uses are coming from the models, which have only annual aggregation of the results. For the purpose of this dissertation these annual results were disaggregated to obtain monthly results, which was described in Sections VII.2 and VII.3. For the analysis presented in this section, monthly energy use data had to be further disaggregated in order to estimate daily values. For space heating and space cooling it was done proportionally to the amount of heating and cooling degree hours during each day in a similar manner as with heating and cooling degree days for calculating monthly energy use, as described in Sections VII.2. For other end-uses the assumption that energy use within the month does not vary significantly from one day to another was made, and, therefore, in order to acquire daily estimations monthly energy use values were divided by the number of days in the month.

January was chosen as a month, which can illustrate two interesting situations when energy storage can be needed the most: during peak demand for space heating energy in the Northern Hemisphere and peak demand for space cooling - in the Southern Hemisphere.

Figure 59 and Figure 60 present daily results for thermal energy use versus solar thermal energy per square meter of floor area, which can be potentially produced in different building types of NAM and WEU, respectively.

It can be seen that in the building types with typically low or medium height short-term (2-4 days) storage can play an important role for reducing or eliminating need for back-up energy supply. For example, in both regions in single-family buildings there are few days in January, when produced solar heat is not sufficient for covering space and water heating energy use. However, the excess solar thermal energy produced during several previous days, if stored with low thermal losses, can cover substantial portion of this energy demand (in case of NAM it is likely that energy needs can be fully satisfied with solar during all the days). Similar situation can be observed in retail buildings in NAM, while in WEU this building type, as well as buildings in ‘other’ category, do not demonstrate the need for auxiliary energy supply, as the results show that the amount of solar thermal energy, which can be produced in these building types can be sufficient to cover energy demand for space heating and hot water during all days.

Results for WEU show that short-term energy storage may be important for other building types in this region, such as educational buildings, hospitals, hotels and restaurants. The January profile for these building types (Figure 60) demonstrates that there are several days when the amount of produced solar heat is not enough to cover daily thermal energy needs. At the same time production during previous days of the month is characterized by notable amount of excessive solar heat, mostly due to lower energy needs for space heating (caused by higher ambient temperatures). This heat, if stored efficiently, can be utilized during those colder days with higher demand for space heating. It can significantly reduce need for additional energy sources or in some cases (e.g. educational buildings) cover energy needs by solar to full extent.

In NAM these building types, as well as buildings belonged to ‘other’ category, typically have higher heights and, therefore, smaller roof areas available for solar technologies in relation to heated floor area, than in WEU. Consequently, these building types demonstrate daily energy profiles much similar to high-rise building types, such as multifamily and office buildings. Daily profiles for these building types in NAM, as illustrated in Figure 59, show that during most of the days daily solar thermal energy generation can satisfy only certain part of daily energy needs for space and water heating (with exception of several days, where thermal energy use can be fully covered by solar energy in educational and ‘other’ buildings, as well as in hotels &

restaurants). In WEU multifamily and office buildings short-term energy storage is unlikely to significantly help with satisfying thermal energy needs, as the amount of produced excessive solar heat is relatively small and there is a number of cold days during the month, when energy use is considerably higher than the amount of potentially produced solar thermal energy.

As for electricity demand and solar electricity supply, several building types in AFR region demonstrate potential for achieving energy plus level (Figure 61). For example, in single-family, educational buildings, hotels & restaurants, retail and 'other' buildings solar electricity solar electricity can be produced in the amount, which exceeds electrical energy needs during all days of the month. In office and multifamily buildings, on the contrary, daily solar electricity production is not sufficient to cover daily electricity use for every day (diurnal storage for solar electricity would not provide any additional benefits in terms of increasing solar fraction).

In LAC region besides single-family and retail buildings (which typically have the highest solar potential due to building geometry), multifamily buildings as well have the opportunity to cover electricity demand with solar energy during all months and even produce certain amount of excess solar electricity. In commercial building sub-categories (except for retail buildings) solar electricity produced during each day cannot cover daily electricity demand, which is to large extent can be explained by much higher energy intensities for commercial lighting in comparison to AFR region. Short-term storage for solar electricity for these building types can hardly be an optimal solution, unless lighting electricity demand is significantly reduced.

This section has demonstrated that short-term storage can be a beneficial option for certain building types. These building types usually include medium-rise buildings (e.g. hospitals, hotels & restaurants, etc. – depending on the region). Typically single-family and retail buildings can cover daily thermal and electrical energy demand without the need for storage. High-rise buildings, such as multifamily and office buildings, may not benefit from the short-term storage, as they usually consume all the solar energy produced during each day.

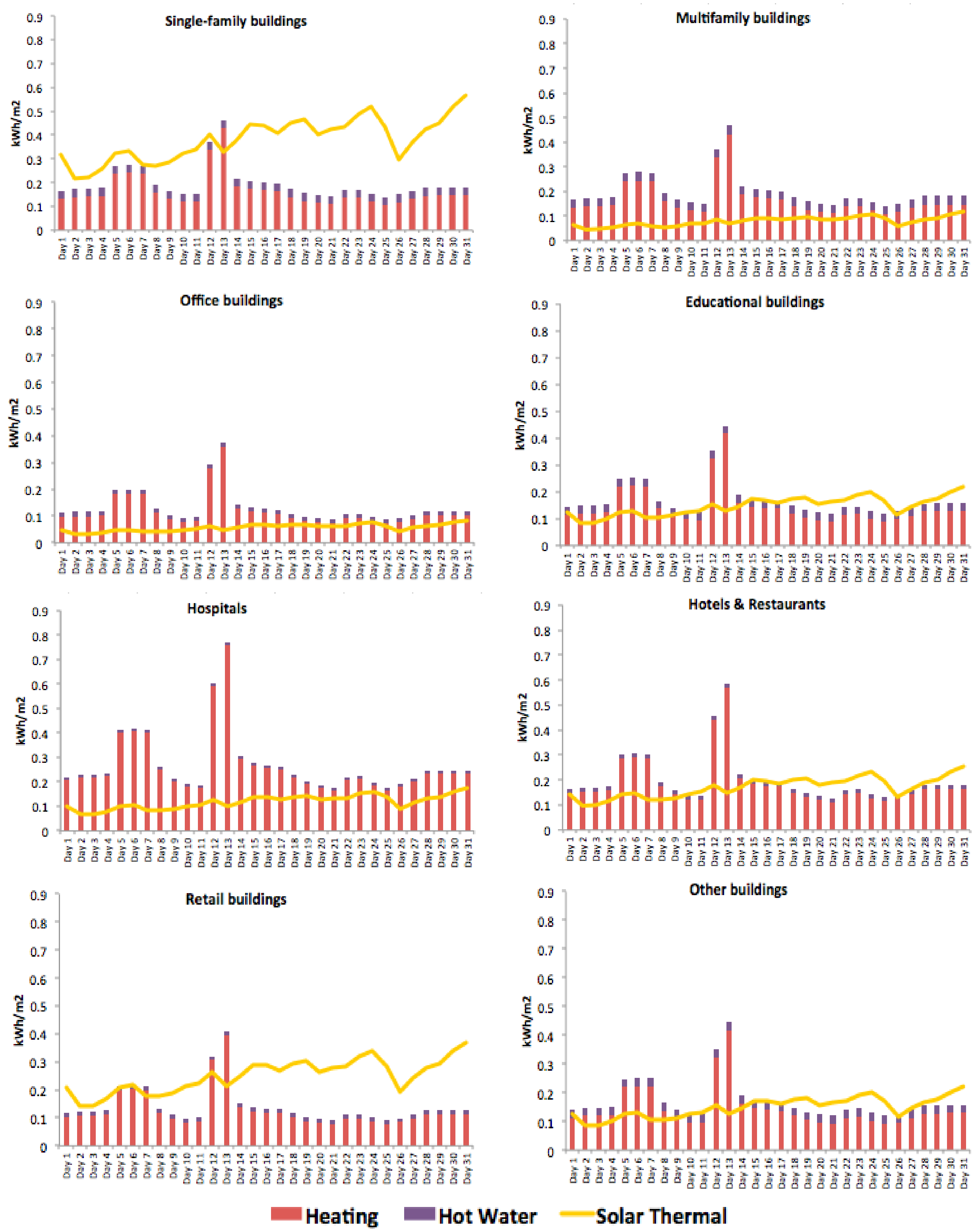


Figure 59. Energy use for space heating and water heating and potential solar thermal energy supply per square meter of the floor area for every day of January 2050 for different building types in NAM region under Deep scenario

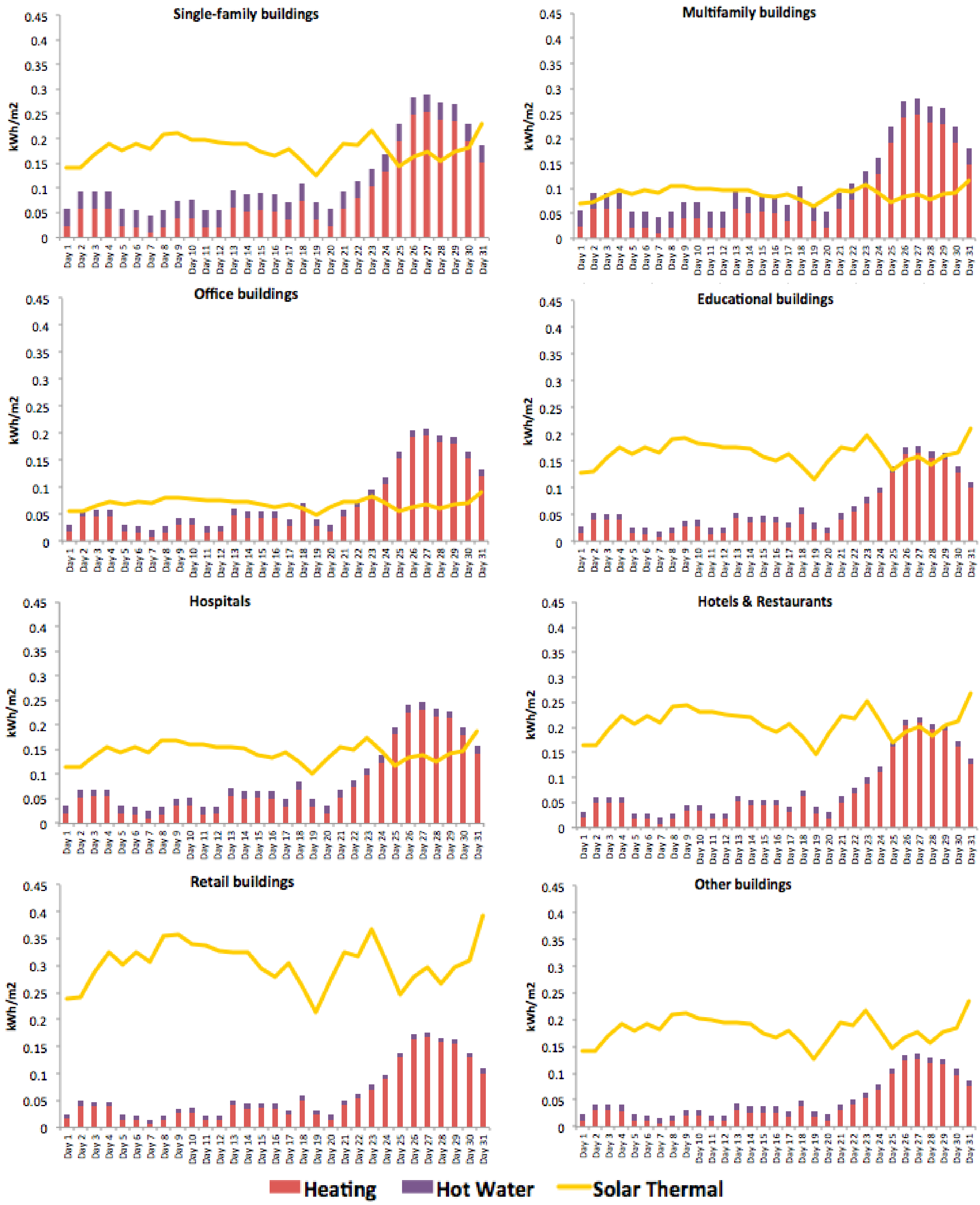


Figure 60. Energy use for space heating and water heating and potential solar thermal energy supply per square meter of the floor area for every day of January 2050 for different building types in WEU region under Deep scenario

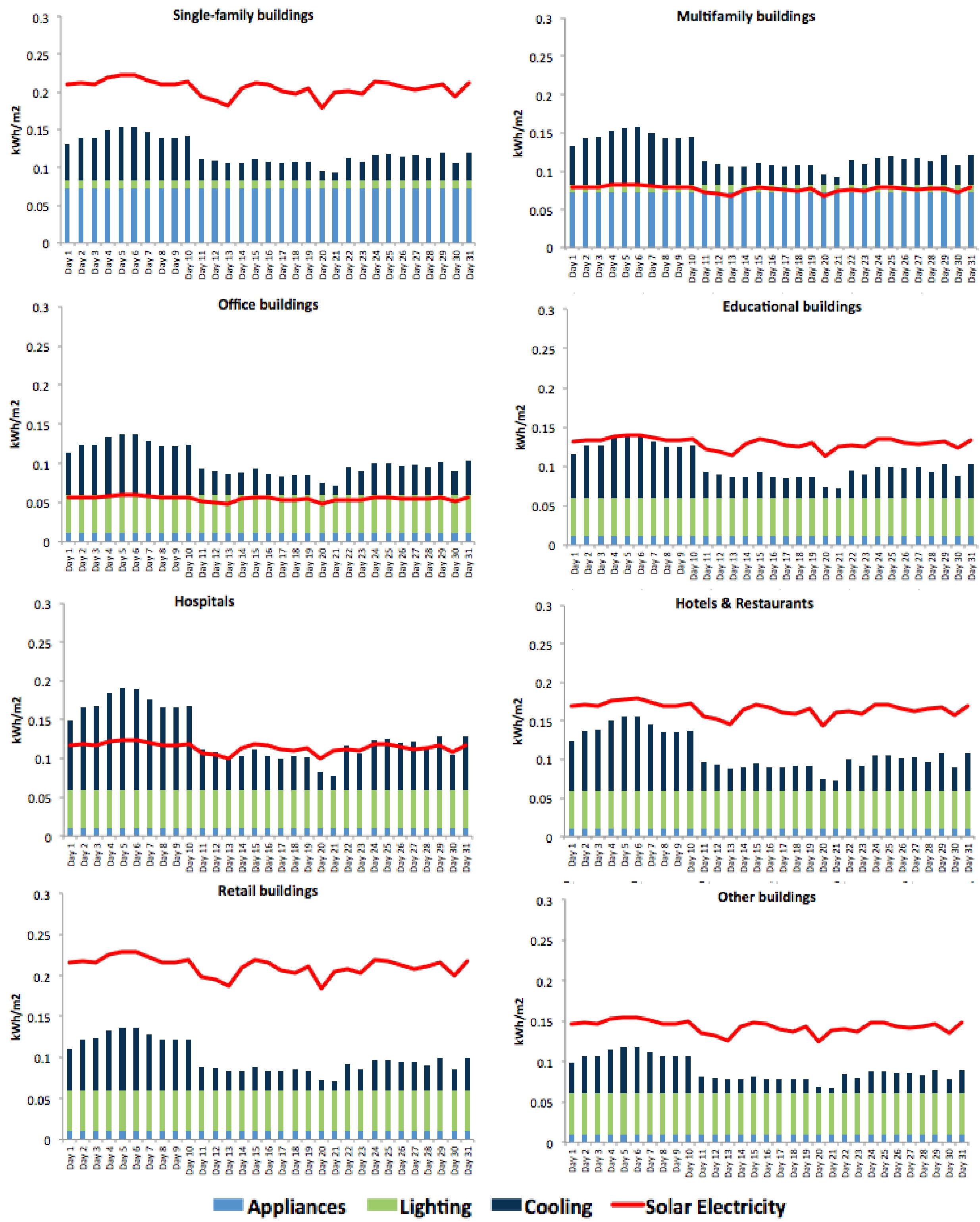



Figure 61. Energy use for space cooling, appliances, lighting and potential solar electrical energy supply per square meter of the floor area for every day of January 2050 for different building types in AFR region under Deep scenario

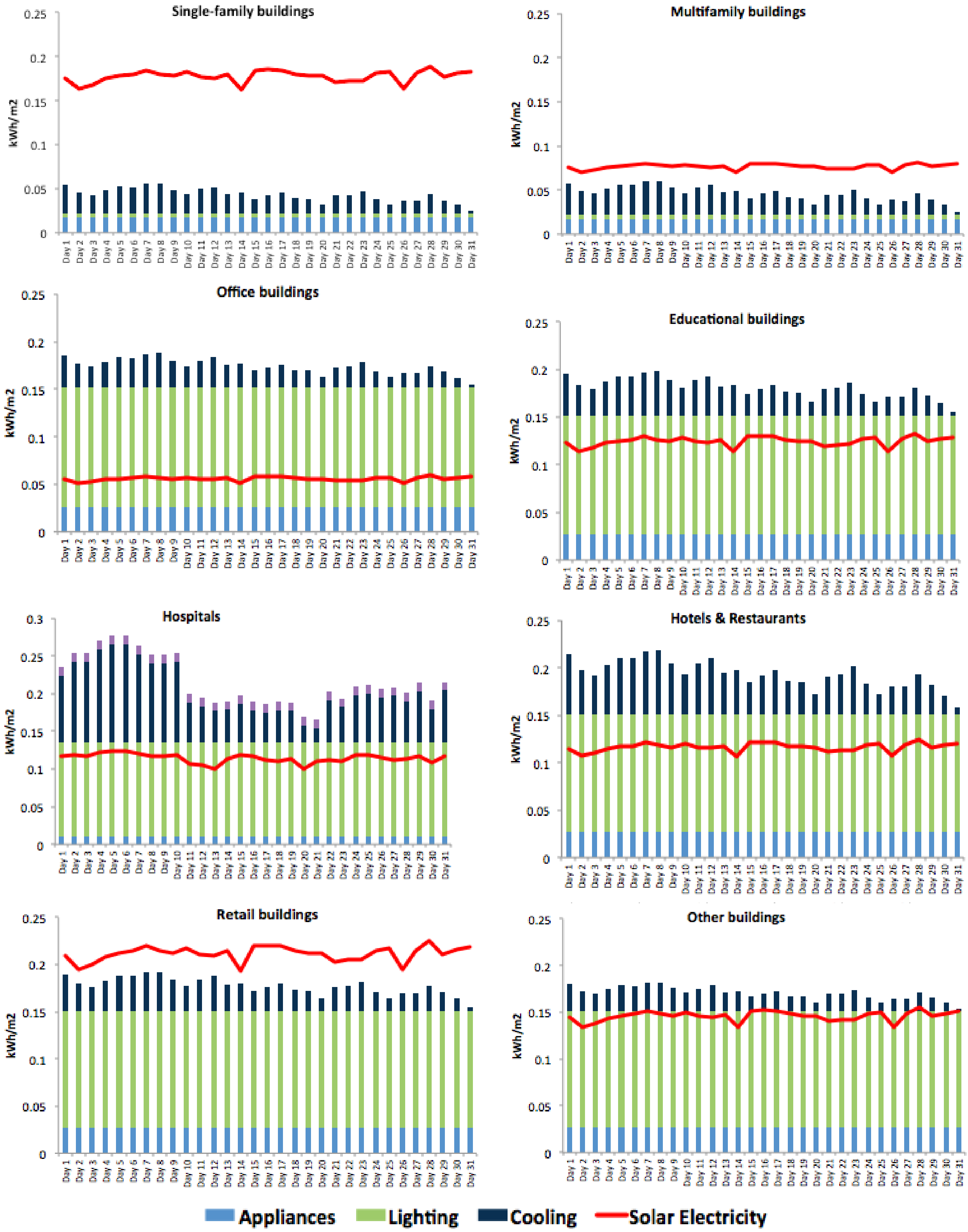



Figure 62. Energy use for space cooling, appliances, lighting and potential solar electrical energy supply per square meter of the floor area for every day of January 2050 for different building types in LAC region under Deep scenario

## VIII.7 Efficient appliances and lighting are crucial for NZEBs: sensitivity analysis for respective energy intensities

**KEY MESSAGE**:
Moderately efficient lighting systems and appliances make it impossible to cover all electricity needs with solar energy in most of commercial and public building categories and residential buildings, respectively, which makes high efficiency of these systems crucial for NZEBs

As it has been noted above, energy intensities for appliances and lighting in this study are coming from the business-as-usual scenario of BUENAS model. As this scenario does not assume significant energy efficiency improvements, it is important to explore how energy use reduction for these end-uses may influence the potential to cover electricity needs by solar energy generation.

In pursue of this idea a sensitivity analysis was conducted, during which different levels of energy intensities for appliances and lighting were examined. The results are presented for four selected regions (NAM, WEU, SAS, CPA) and three building types (single-family, multifamily and offices) in **Figure 63 -** for appliances and in **Figure 64 -** for lighting.

**Figure 63** shows that variation in the energy intensities for appliances plays an important role in residential buildings. For example, reduction of energy intensities for appliances in single-family buildings of North America by 50% makes the achievement of full coverage much more possible: the number of months, in which electricity use can be covered by solar electricity increases from 8 to 10 in comparison to the baseline. In multifamily buildings of this region even 50% reduction in the appliances energy intensities will not remove the necessity of the supplementary energy supply during all the months, but will increase the portion of electricity use, which can be covered by solar.

In Western Europe highly energy efficient appliances alone (i.e. 50% reduction in energy intensities) will not ensure that solar electricity can be utilized as a single source of energy in all three building types, but such a reduction significantly increases the share of electricity, which can be covered by on-site solar generation. On the contrary, if the energy intensities of appliances increase by 25%, solar electricity will not be sufficient even in single-family buildings during all the months.

In CPA region energy efficient appliance play an important role in multifamily buildings, as 50% reduction in their energy intensity halves the need for electrical supply from other sources during the year. In single-family buildings in this region reduction in the energy demand for appliances is less crucial, as already with the base energy intensities electricity needs can be satisfied by solar energy in all months. A similar picture can be seen in the SAS region: in single-family buildings it is possible to produce solar electricity sufficient to cover electricity use in all months even if appliances energy intensities increase by 50%.

In SAS in all building types the variations in appliances' energy intensities have a much smaller impact than in other regions. It can be explained by the fact that in SAS cooling is playing the dominant role in the electricity, consuming 65% of the 2050 electricity in residential and 51% - in office buildings, while appliances are responsible for only 26% and 9% for residential and office buildings, respectively (see Figure 65).

In other three regions, however, appliances have the largest shares in residential buildings among other electrical end-uses (56% in NAM, 66% in WEU and 86% in CPA), which explains high sensitivity of the total electricity use to the variations in the appliances' energy intensities. Office buildings have relatively low share of energy use for appliances in the electricity mix (from 9% in SAS to 28% in WEU – see Figure 65), and, therefore, the impact of changes in the appliances' energy intensities on the results for the office buildings is relatively small in all analyzed regions.

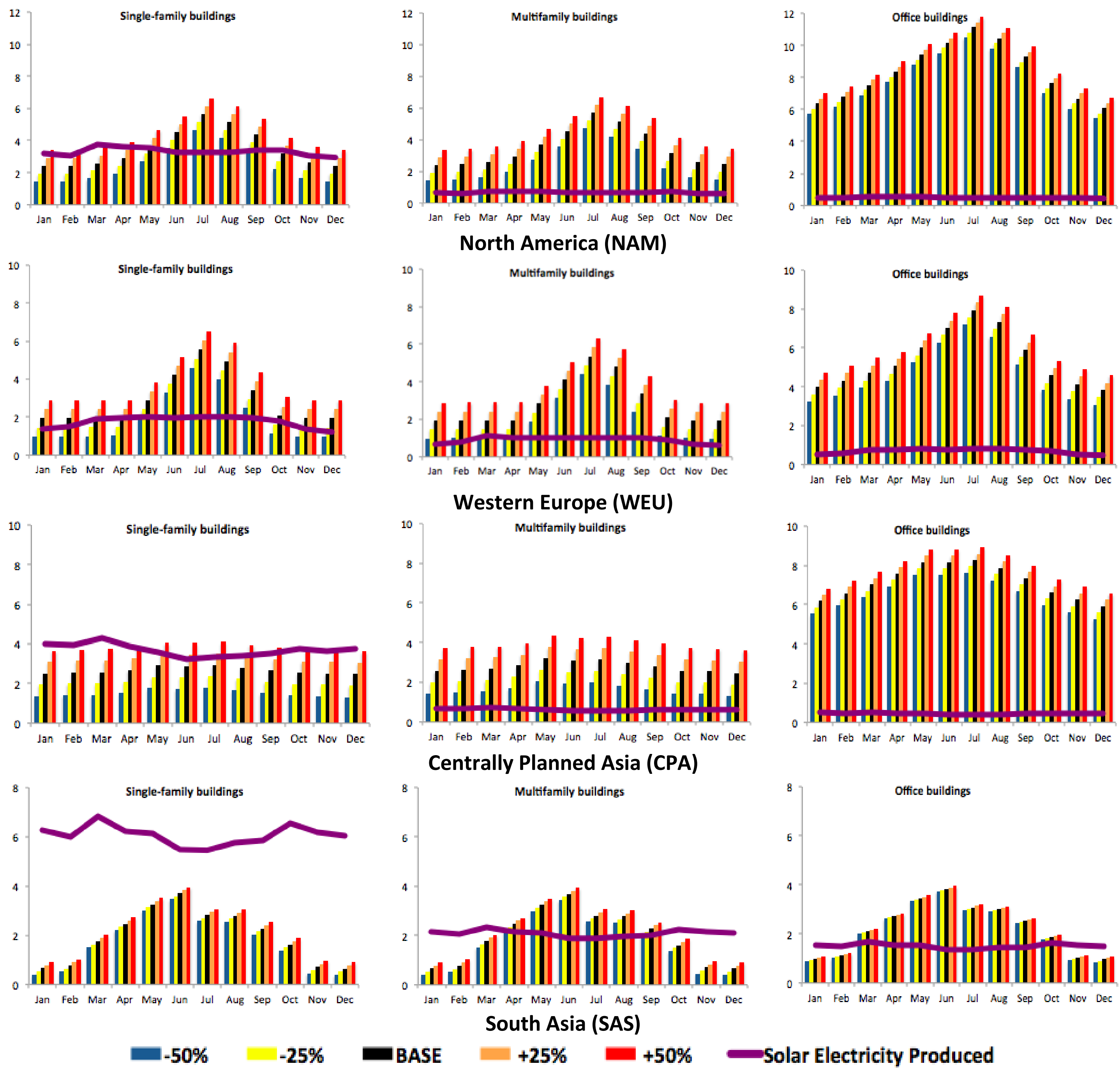



Figure 63. Role of the appliances' efficiency in covering electrical energy needs with solar electricity in selected regions under Deep scenario, kwh/m$^2$ of floor area

*Note*:

- BASE – the level of energy intensities for appliances assumed in this study based on the results from BUENAS model;
- -25%, -50% - decrease in energy intensities for appliances by 25%, 50%, respectively;
- +25%, +50% - increase in energy intensities for appliances by 25%, 50%, respectively.

Figure 64 shows that variation of the energy intensities for lighting has a notable impact on the total electrical energy use in office buildings, while in single-family and multifamily ones its role is less significant. It can be explained by the fact that lighting has the major share in the electricity use of the office buildings in all four regions, while in the residential buildings it is quite small, as it can be seen in Figure 65.

However, in all building types, even in the office buildings, variation in the lighting energy intensities does not significantly increase chances for covering electricity demand by solar electricity. Only in SAS office buildings notable improvement of lighting energy efficiency increases the number of the months, in which the full solar coverage is possible. In other regions lower energy demand for lighting simply increases the share of the energy use, which can be supplied through solar electricity in each month.

The results presented in this section vary to a great extent among regions and building types, however, the most important common implication is that increase in energy efficiency of lighting and appliances is essential for increasing solar fraction and driving buildings towards NZE target. That also means that the improvement of energy efficiency of the building envelope alone is usually insufficient for achieving net-zero energy balance. Therefore, ambitious policies aimed at increasing building energy performance should be introduced in a package, which should include regulations (e.g. performance-based building codes), economic incentives, educational and training programs for building professionals, as well as other well-enforced policy instruments, enhancing the efficiency of appliances and equipment (e.g. product standards and labeling), as well as, lighting systems (e.g. phasing out of inefficient light bulbs from the market, installation of movement controls, etc.).

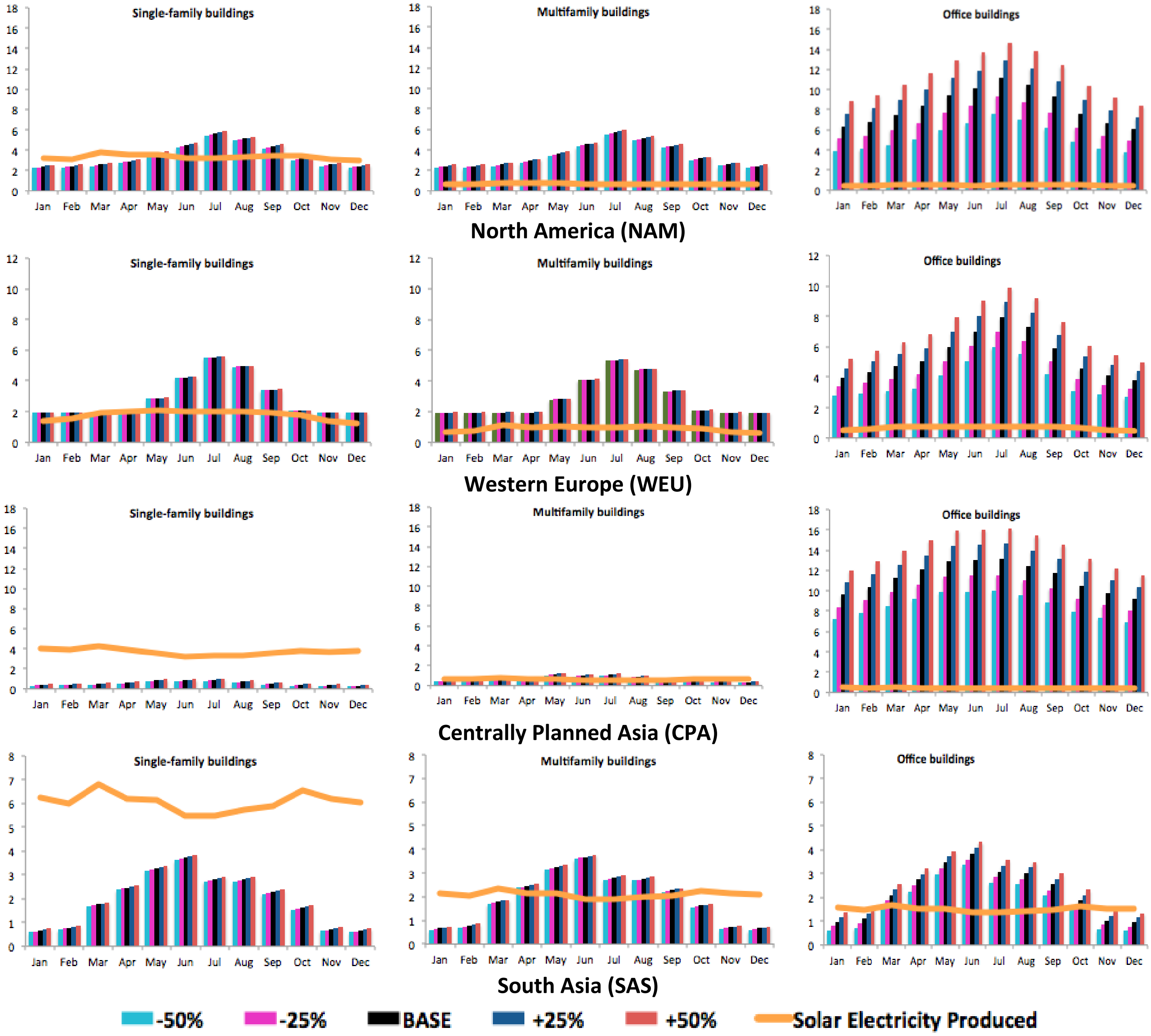



Figure 64. Role of the lighting efficiency in covering electrical energy needs with solar electricity in selected regions under Deep scenario, kwh/m$^2$ of floor area

*Note*:

- BASE – the level of energy intensities for lighting assumed in this study based on the results from BUENAS model;
- -25%, -50% - decrease in energy intensities for lighting by 25%, 50%, respectively;
- +25%, +50% - increase in energy intensities for lighting by 25%, 50%, respectively.

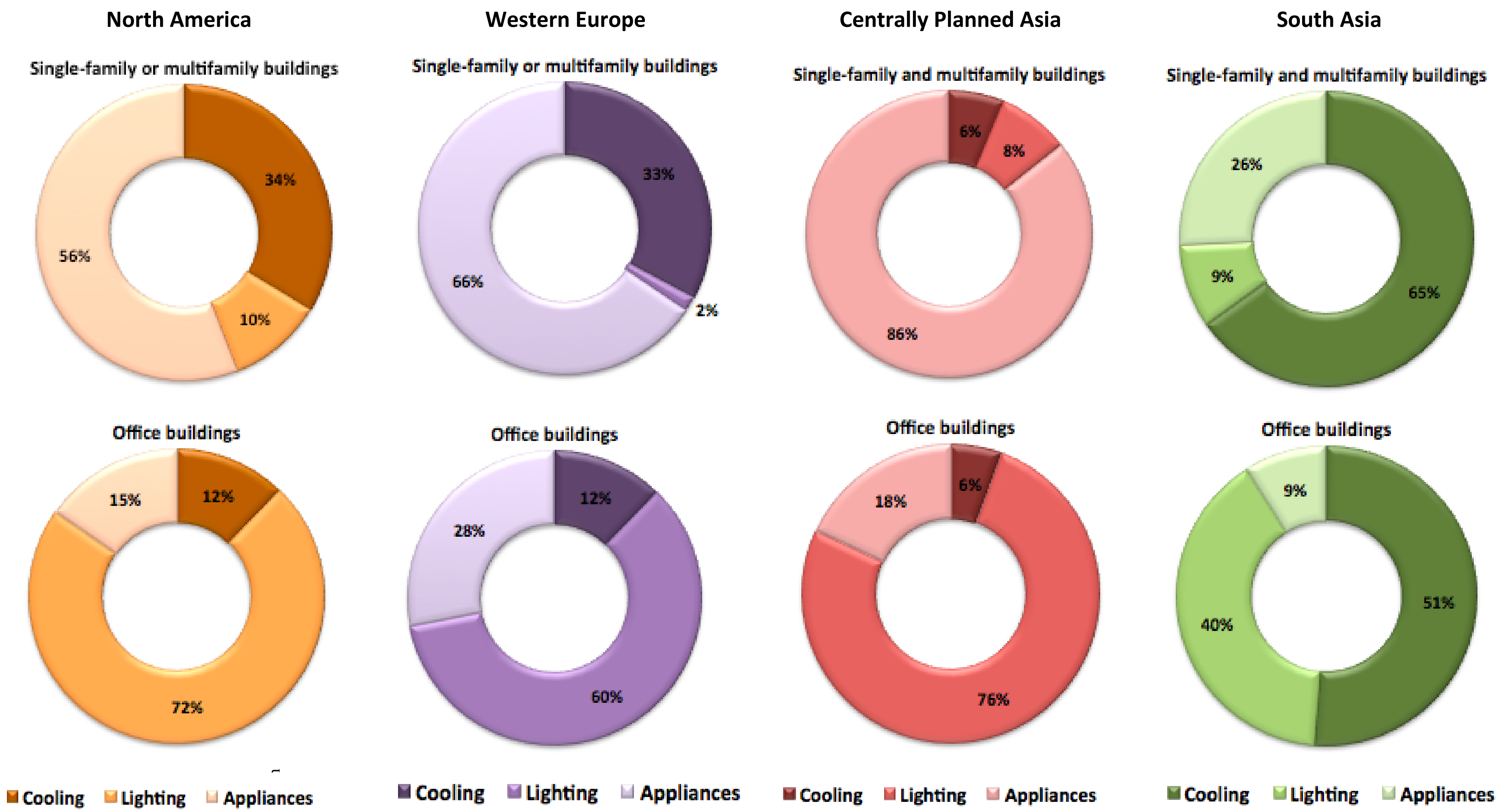



Figure 65. Share of different end-uses in the 2050 electrical energy use for different building types and four selected regions under the Deep scenario

## VIII.8 Larger unshaded roof areas increase potential solar energy supply: sensitivity analysis for roof shading factors

**KEY MESSAGE**:
The larger the roof area, which is available for the solar systems installation and not shaded, the more solar energy can be produced from this roof area and the higher the share of building energy use, which can be covered by solar.

Amount of solar energy, which can be produced by building-integrated technologies directly depends on the available roof area for the installation of the systems. The available roof area presumes that the system can be technically installed on the roof surface and can be exposed to the sunlight, i.e. it should not be shaded by other objects. However, in most of the cases a certain part of the roof is shaded by other buildings, vegetation or other objects, which reduces the roof area, from which solar energy can be produced. Usually low-rise buildings are more likely to have larger portion of the roof area shaded by higher objects, than taller buildings. Also, when the building density is higher (for example, in the urban centers), the possibility for more significant shading increases. In the BISE model this phenomenon is tackled by the application of the shading factors specific for different building types in urban and rural areas (see Section VI.1.3 for more details).

As the shading factor can be quite uncertain and the share of unshaded roof area can be varied through building and urban design, it is important to explore the influence of shading factors on the solar energy output and possibility to cover building energy use with it.

**Figure 66** and **Figure 67** present the results of the sensitivity analysis for solar thermal and solar electric energy output in 2050 under different variations of the shading factors for three building types (single-family, multifamily and educational buildings) and for four selected regions (NAM, WEU, CPA and SAS).

As it can be seen in figures increase in the roof area, available for the solar systems from shading, can influence the results for energy balance significantly. Moreover, the lower height of the building, the higher this impact will be.

In WEU single-family buildings 25% increase in the unshaded available roof area in relation to the base level can help to cover thermal energy uses in all the months, while in the base case three months would require some additional energy supply for the space heating. Although 25% increase in the unshaded roof area does not ensure the achievement of net-zero energy goal in all months (electricity demand is still higher than electrical solar output during several summer months), it decreases the need for the back-up energy use. Moreover, if the excess solar thermal produced during the summer months is used for cooling, it may bring these buildings closer to the net-zero energy goal.

In NAM single-family buildings produce excess amount of solar thermal energy already with the base values for shading factors and the further increase in the roof area will increase the amount of excess solar heat. Therefore, the further increase of the unshaded roof area would make sense if this heat can be utilized in the building, for example, for solar cooling. Alternatively, the installation of another type of the solar system with the maximized electric efficiency can benefit from the increased unshaded roof area. Moreover, such a system will have lower thermal output, which may result in a reduced amount of the excess solar heat.

For CPA and SAS increase in the unshaded roof area of single-family buildings is not needed, as already in the base situation both thermal and electric energy use can be covered by solar energy during all months.

Solar thermal and electric outputs for educational buildings are typically larger than the ones for multifamily buildings in all regions, however, these building types demonstrate similar trends in the reaction of solar outputs to the variations in the shading roof factors.

Having a relatively small roof area in relation to the floor, multifamily and educational buildings would benefit from the reduced shading of the roof. In most of the presented region maximum possible increase of the available roof area will be beneficial for bringing buildings closer to the net-zero energy status. Only in SAS it may magnify the problem of the excess solar heat. In the three regions, except for SAS, in multifamily building even with enlarged unshaded roof areas the need for the supplementary electricity supply will still remain in a number of months.

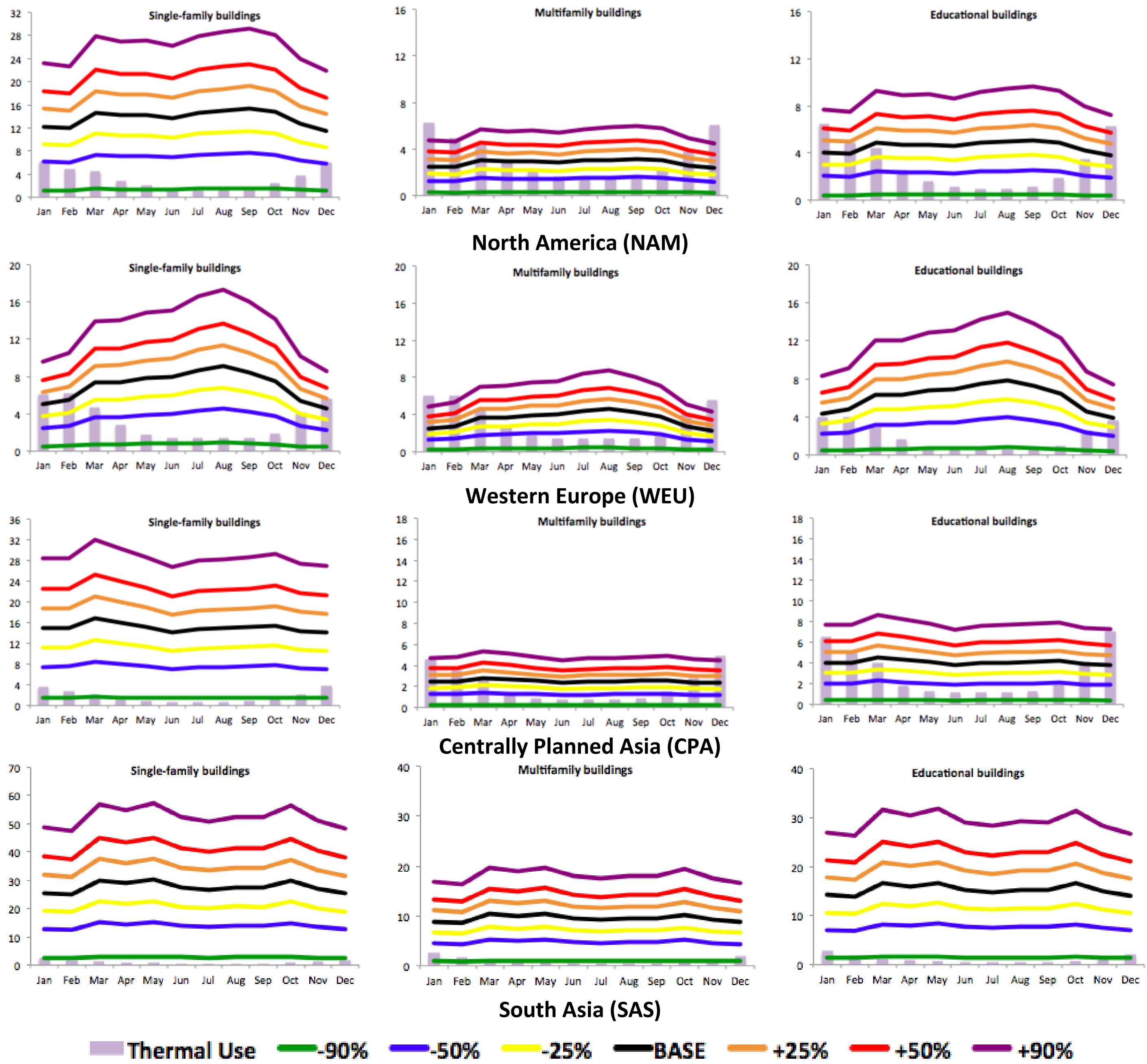



Figure 66. Role of the unshaded roof share available for solar systems in covering thermal energy needs with solar heat in selected regions under Deep scenario

*Note*:

- BASE – level of solar heat with the share of unshaded roof area available for solar systems assumed in this study
- -25%, -50%, -90% - level of solar heat with the decrease in the available unshaded roof area share by 25%, 50% and 90%, respectively, in relation to the base level
- +25%, +50%, +90% - level of solar heat with the decrease in in the available unshaded roof area share by 25%, 50% and 90%, respectively, in relation to the base level.

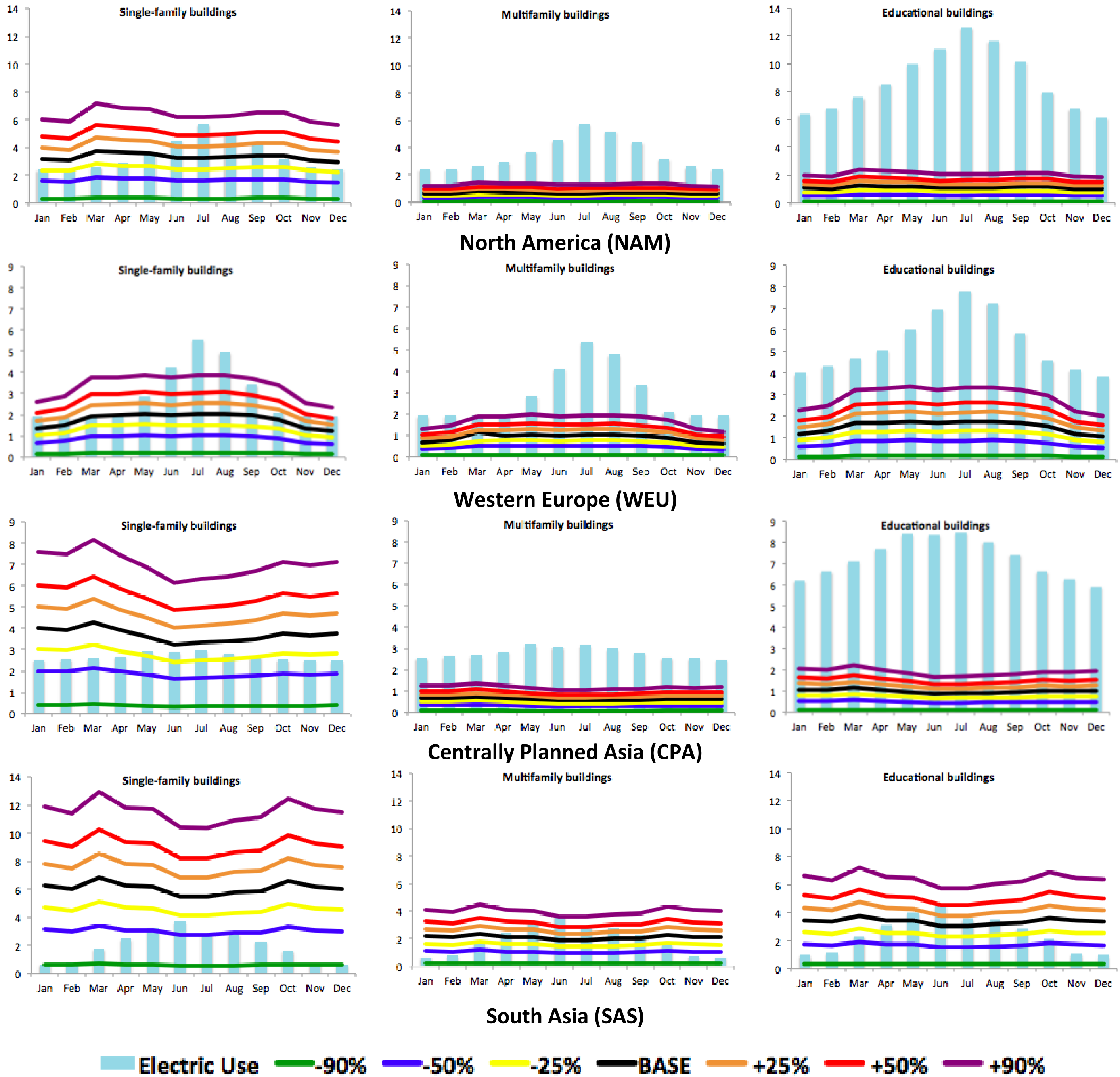



Figure 67. Role of the unshaded roof share available for solar systems in covering electrical energy needs with solar electricity in selected regions under Deep scenario

*Note*:

- BASE – level of solar electricity with the share of unshaded roof area available for solar systems assumed in this study
- -25%, -50%, -90% - level of solar electricity with the decrease in the available unshaded roof area share by 25%, 50% and 90%, respectively, in relation to the base level
- +25%, +50%, +90% - level of solar electricity with the decrease in in the available unshaded roof area share by 25%, 50% and 90%, respectively, in relation to the base level.

## VIII.9 Smaller roof areas available for solar technologies may significantly reduce solar energy potential: sensitivity analysis for roof facility factors

**KEY MESSAGE**:
The roof design should allow for maximization of the roof area available for solar energy systems from other roof facilities, especially in high-rise buildings in order to exploit potential for solar energy production to full extent.

Previous section presented the analysis on how the availability of unshaded roof area for the installation of solar technologies influences the amount of solar energy, which can be produced on the building's site. Results demonstrated that extending roof area, occupied by solar technologies, has a significant impact on the amount of generated solar heat and certain influence on the amount of produced solar electricity.

This section explores the impact of variations in another roof availability factor – roof facility factor, which indicates the share of the roof surface available for the installation of solar systems from other roof facilities – on the amount of solar energy possible to generate on buildings' roofs. As the values for the facility roof factor is quite high (often more than 80% of the roof area is assumed to be available from these facilities), the sensitivity analysis performed in this section mostly explores the effects of reducing this available roof area, which can happen in case of not well-thought roof design.

Figure 69 - Figure 68 demonstrate the results for solar thermal and solar electric outputs, respectively, which can be produced with different roof facility factors. Levels of roof facility factors are calculated as reduction from the base value assumed in this study, except for one case, in which the increase in the available from the facilities roof area is assumed by up to 100%. As in the previous section results of the analysis are presented for four selected regions (NAM,

WEU, CPA and SAS) and three building types (single-family, multifamily and educational buildings).

In a similar way as in the situation with the shading roof factors, described in the previous section, the results for roof facility factors show that in all regions solar energy outputs in single-family buildings are the most sensitive to variations in the roof facility buildings among selected building types.

It can be seen in all the charts that the difference between the solar output with the base values of roof facility factors and the maximum available roof area is not significant. Reduction in the roof facility factors on the solar energy output decreases the share of energy use, which can be covered by solar energy. Sensitivity of the results for energy balance (here: how much of the energy use can be supplied by solar energy) to these reductions varies among different building types and regions.

In NAM even with up to 50% decrease in the roof facility factors solar energy can satisfy thermal energy demand in single-family buildings during the year, however, it will notably reduce the portion of the electricity needs, which can be satisfied with solar electricity. In WEU any loss in the available roof area will aggravate the necessity in the additional heating sources during the winter months and auxiliary electricity supply in all the months (although most of the back-up electricity would be needed for cooling during the warm period of the year). In CPA and SAS only 90% reduction in the available roof area can lead to the situation, when the additional source of thermal energy would be needed in this building type. Some electrical back-up in single-family buildings in these regions might be needed in case the available from facilities roof area is halved.

For multifamily and educational buildings any reductions in the roof area available from the facilities for solar systems installation is quite undesirable as it will intensify the need for auxiliary energy demand for both electricity and heat in all regions, except for SAS, where significant energy back-up would be required only for electrical end-uses. For the building types, which have a relatively small roof area in relation to the floor area, from which energy consumption is taking place, any loss in the availability of roof area and, consequently, solar system surface exposed to the sunlight, limits the possibility to achieve net-zero energy goal solely with solar energy and increases the need for the back-up from alternative energy sources.

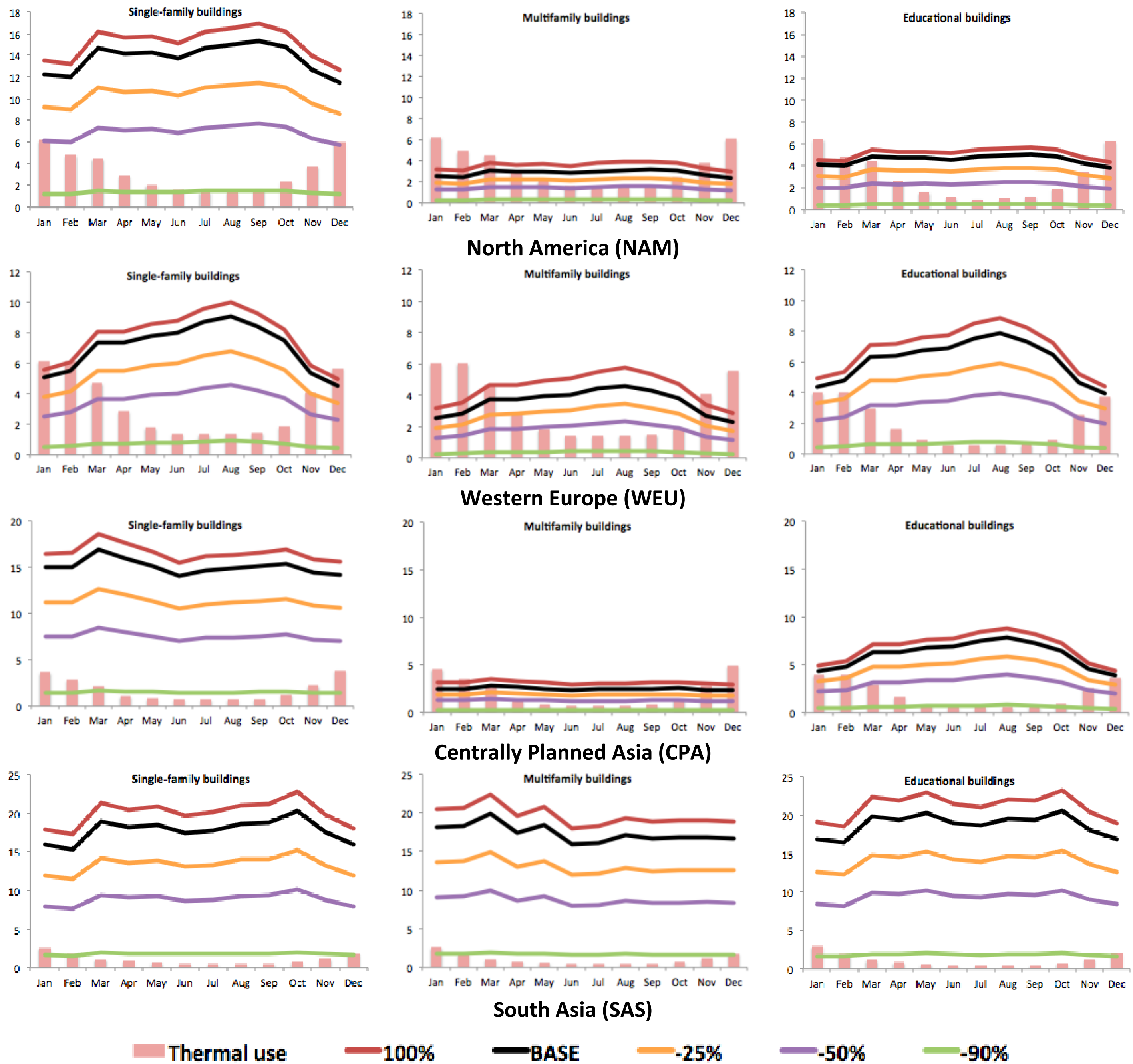



Figure 68. Role of the roof share available for solar systems from the roof facilities in covering thermal energy needs with solar heat in selected regions under Deep scenario

*Note*:

- BASE – level of solar heat with the share of roof area available from the facilities for solar systems assumed in this study
- 100% - level of solar heat with the whole roof area available from the facilities for solar systems
- -25%, -50%, -90% - level of solar heat with the decrease in the roof share available from the roof facilities by 25%, 50% and 90%, respectively in relation to the base level.

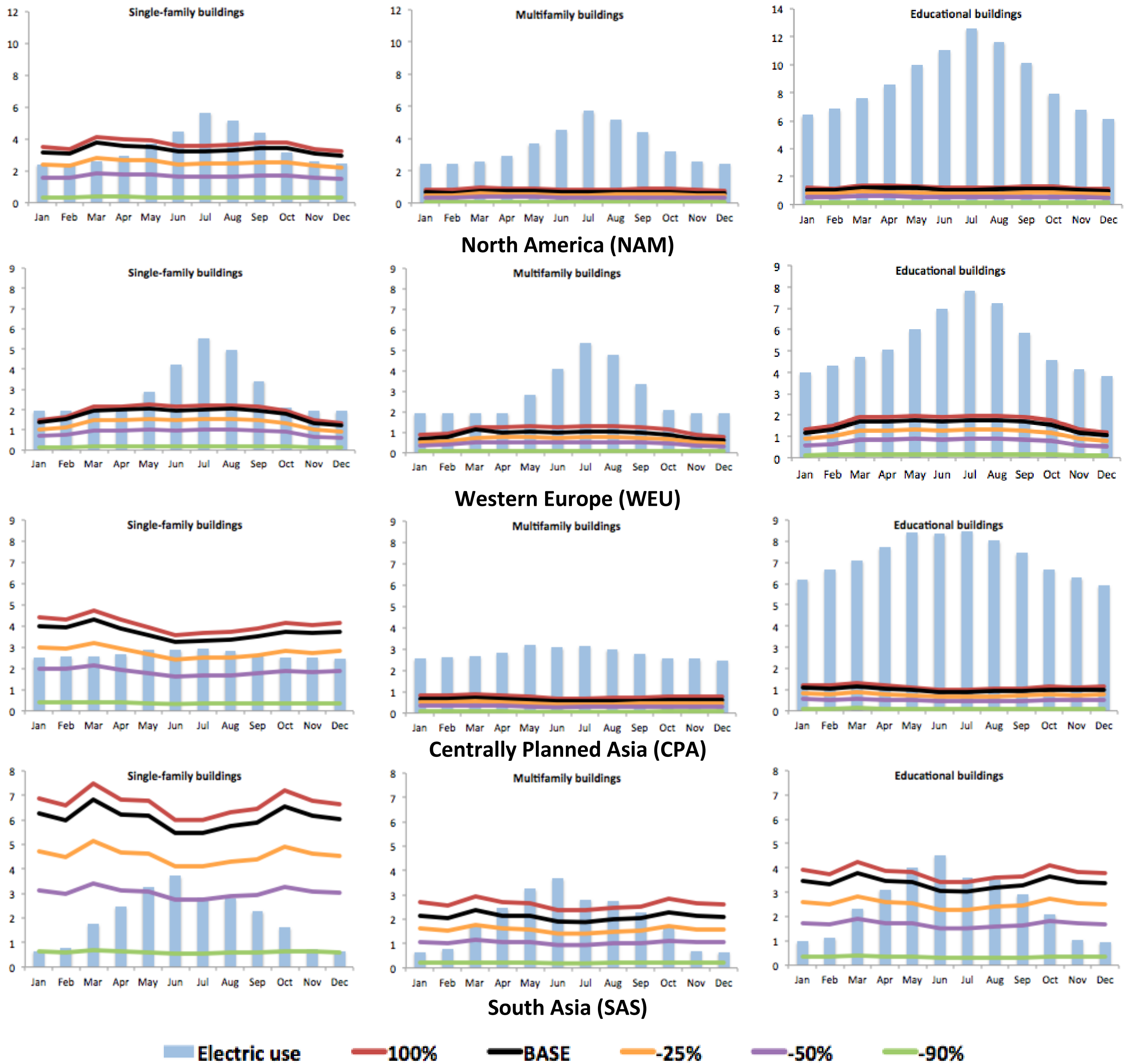



Figure 69. Role of the roof share available for solar systems from the roof facilities in covering electrical energy needs with solar electricity in selected regions under Deep scenario

*Note*:

- BASE – level of solar electricity with the share of roof area available from the facilities for solar systems assumed in this study
- 100% - level of solar electricity with the whole roof area available from the facilities for solar systems
- -25%, -50%, -90% - level of solar electricity with the decrease in the roof share available from the roof facilities by 25%, 50% and 90%, respectively in relation to the base level.

## VIII.10 A number of building types and climate zones demonstrate high potential for solar-supplied NZEBs

**KEY MESSAGE**:
Global picture shows a number of locations, in which NZE goal can be achieved in a number of building types solely with on-site solar energy production. However, high-rise NZEBs seem to be impossible in most of the locations in the world

This section aims at presenting results for the whole world by means of customized visualization tool, which is a part of BISE model. This visualization tool was developed based on the Windows Presentation Foundation (WPF)[34] framework with the aim to present numerical results of BISE model for different scenarios, regions, climate zones and buildings types in colorful dynamic maps, which show changes in the results over years or months, or both. The best way to present trends in the results is by means of video files, which reflect very well the change over time in the same geographical areas. This section presents both videos and static maps (in case some computers do not allow for viewing the video) for certain years, which depict the potential coverage of building energy use by building-integrated solar energy generation in different building types.

Figure 70 - Figure 73 present the results on the potential coverage of building energy needs by solar energy (separately for thermal and electric) in 2050 under Deep scenario for four selected building types (results for remaining building types can be found in Annex E, Section XV.1, Figure 103 - Figure 106). In this section we will focus on the results for single-family, multifamily, office and educational buildings.



[34] Windows Presentation Foundation (WPF) is a next-generation presentation system for building Windows client applications with powerful visualization opportunities. The primary goal of WPF is to help developers create attractive and effective user interfaces. The core of WPF is a resolution-independent and vector-based rendering engine that is built to take advantage of modern graphics hardware. WPF extends the core with a comprehensive set of application-development features that include Extensible Application Markup Language (XAML), controls, data binding, layout, 2-D and 3-D graphics, animation, styles, templates, documents, media, text, and typography. WPF is included in the Microsoft .NET Framework (Microsoft 2014).

In case of the solar thermal energy, there is a substantial potential to cover energy needs with solar energy for all presented building types during the warm season in most of the locations. The main reason for this is reduced heating load in buildings during this time period. Among all building types single-family buildings demonstrate the highest potential to cover thermal energy needs in all presented months. This difference is especially noticeable in the Northern Hemisphere in July, where for single-family buildings all thermal energy needs can be covered by solar energy, except for some Scandinavian countries, while for multifamily, office and educational buildings this potential is far from reaching 100% target in a number of locations (e.g. Canada, coldest part of Russia, mountainous areas of China, etc).

Results for January demonstrate that all building types have a clear need for axillary thermal energy supply in a large part of the Northern Hemisphere. These results clearly show the impact of climate conditions on the energy balance in buildings: coldest climates have the highest heating load, which is very hard (or in many cases impossible) to cover only with solar energy. Results for October show similar trends, although in most of locations the share of thermal energy use, which can be covered by potential solar heat supply is larger than that in January, as demand for space heating energy in this part of the world is typically lower than in January.

Buildings located in Southern Hemisphere generally have much lower energy demand for space heating and very often for hot water as well. At the same time these areas usually have higher number of sunny hours throughout the year in comparison to the Northern part of the world. These two factors lead to the fact that in the Southern hemisphere solar thermal energy produced in buildings in most cases can be sufficient to cover building thermal energy needs.

For solar electricity the results are quite different from those for solar thermal energy outlined above. In single-family buildings (Figure 70) it is possible to achieve 100% coverage for electric energy needs in a number of locations during the cold season. Exceptions are Canada, Europe and Australia. In these countries energy needs for lighting and appliances assumed in BUENAS model are significant for all the months. Moreover, first two regions have rather limited availability of solar energy resources during the winter, which decreases the opportunity to cover electrical needs to full extent. Although Australia much higher availability of solar resources, January in this country is characterized by notable cooling demand, which increases total need for electricity and, therefore, makes available solar electricity supply insufficient to cover all energy needs. In comparison to January in October more locations around the world demonstrate larger solar fraction than in January, due to higher solar activity in the Northern hemisphere and lower demand for cooling in the Southern hemisphere.

During the summer-time the potential to get to net-zero through on-site solar energy generation in single-family buildings decreases in many regions in the Northern hemisphere (e.g. North America, Europe, Northern Africa, Middle East, etc.), as relatively high energy needs for lighting and appliances become accompanied by increased cooling load.

General trends in monthly variations in building energy balance described for single-family buildings are usually similar to the ones in office, multifamily and educational buildings. However, these building types demonstrate much lower potential to cover electricity needs with solar energy than single-family ones in all the months due to the reasons discussed above (i.e. lower available roof area in relation to high energy needs for appliances, lighting and cooling).

In peak months for cooling demand multifamily buildings (Figure 71) demonstrate potential to cover between 5 and 100% of electricity use with solar energy depending on the location. However, the areas where full coverage can be achieved are limited to some parts of Latin American and Pacific islands. Office buildings (Figure 72) are estimated to have even lower solar fraction (approximately 5 – 60%), especially in developed countries. It can be explained by typically higher buildings of this type and large number of sky-scrappers in these regions than in developing countries. Office energy consumption in developed regions is also characterized by higher energy intensities for lighting (see Figure 27), which reduces the potential solar fraction.

Results for educational buildings (Figure 73) for a number of regions show higher solar electric potential in comparison to office buildings (e.g. Africa, India, Australia, Latin America, etc.). However, in most of the regions in the Northern part of the world the portion of electrical energy use, which can be covered by solar is quite low (5 – 30%) throughout the year.

Last part of this section presents several videos (Video 1 - Video 16) on the monthly dynamics in the potential coverage of thermal and electric energy use in buildings by solar energy supply in the four selected building types. These videos show changes over the months of the year 2015 and the year 2050. It can be seen than in 2015 solar fraction is much lower than in 2050, as 2015 is in the very beginning of the transition period (according to the model's assumptions, solar systems start to be installed in new and retrofit buildings in 2014 and by 2025 solar systems will be installed in all such buildings). At the same time specific energy consumption for space heating and cooling, as well as water heating in 2015 is much larger than in 2050, as, according to the assumption for Deep scenario of 3CSEP-HEB model, the share of advanced buildings is increasing in the floor area of new and retrofit buildings from 2013, reaching its maximum only by 2023. Therefore, the picture changes substantially by 2050, when both energy efficiency and solar energy potentials are realized in buildings.

This section has presented the global picture for potential achievement of NZE goal in different building types and locations. It has demonstrated an attempt to bring a dynamic vector into presentation of the results, as they vary greatly both across years and months within each year. The author believes that it is the optimal way for analysis of building energy balance on such a large scale, as it allows for capturing the difference in energy use patterns and solar energy potential among different building types, impacts of climate conditions and time of the year, as well as influence of regional economic development on the energy consumption (e.g. difference between developed and developing countries).

Videos presented in this section can be also watched on youtube (links in Annex F, page 355).

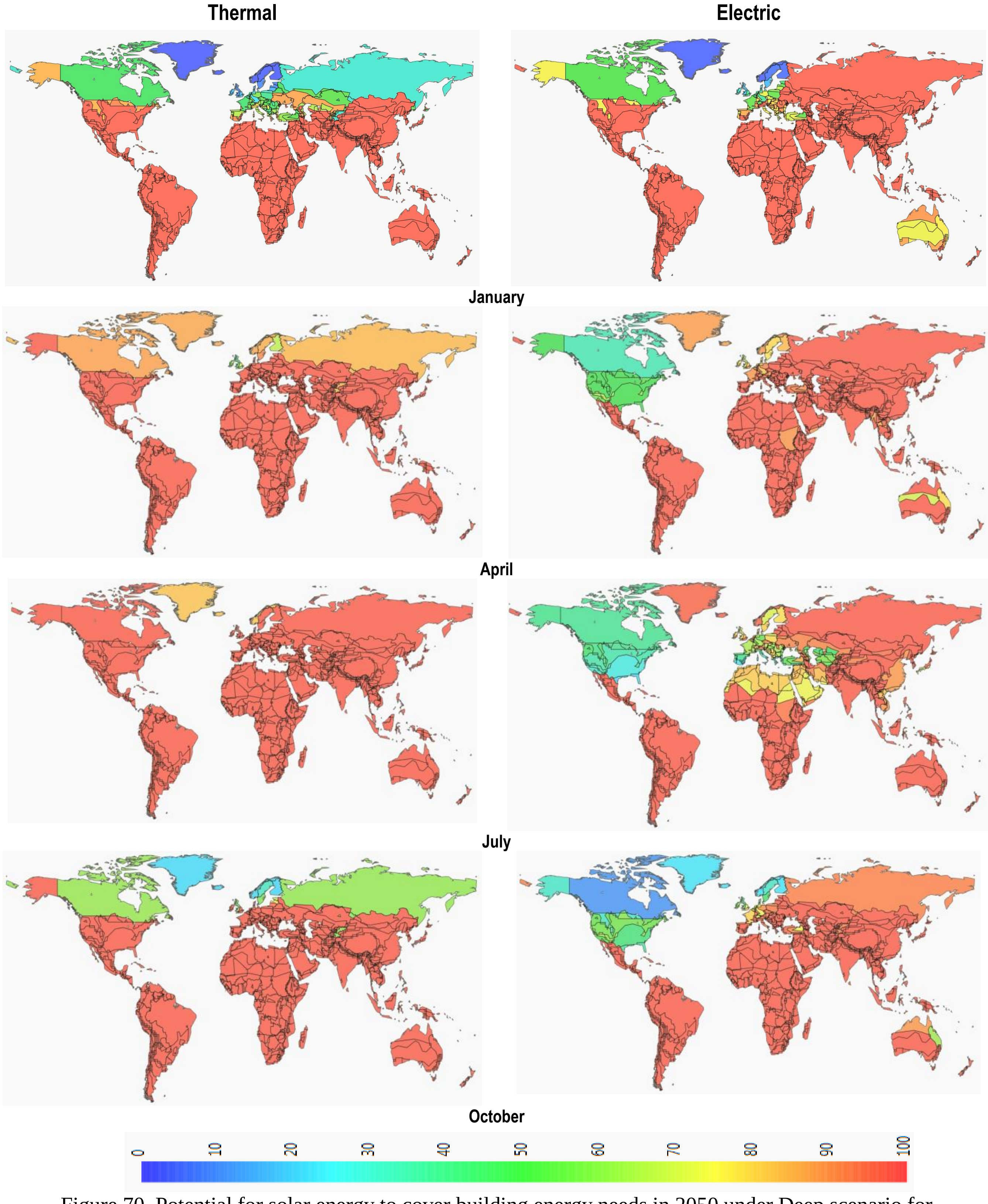



Figure 70. Potential for solar energy to cover building energy needs in 2050 under Deep scenario for single-family buildings

*Note*: the legend shows the share of energy use, which can be covered by solar energy production

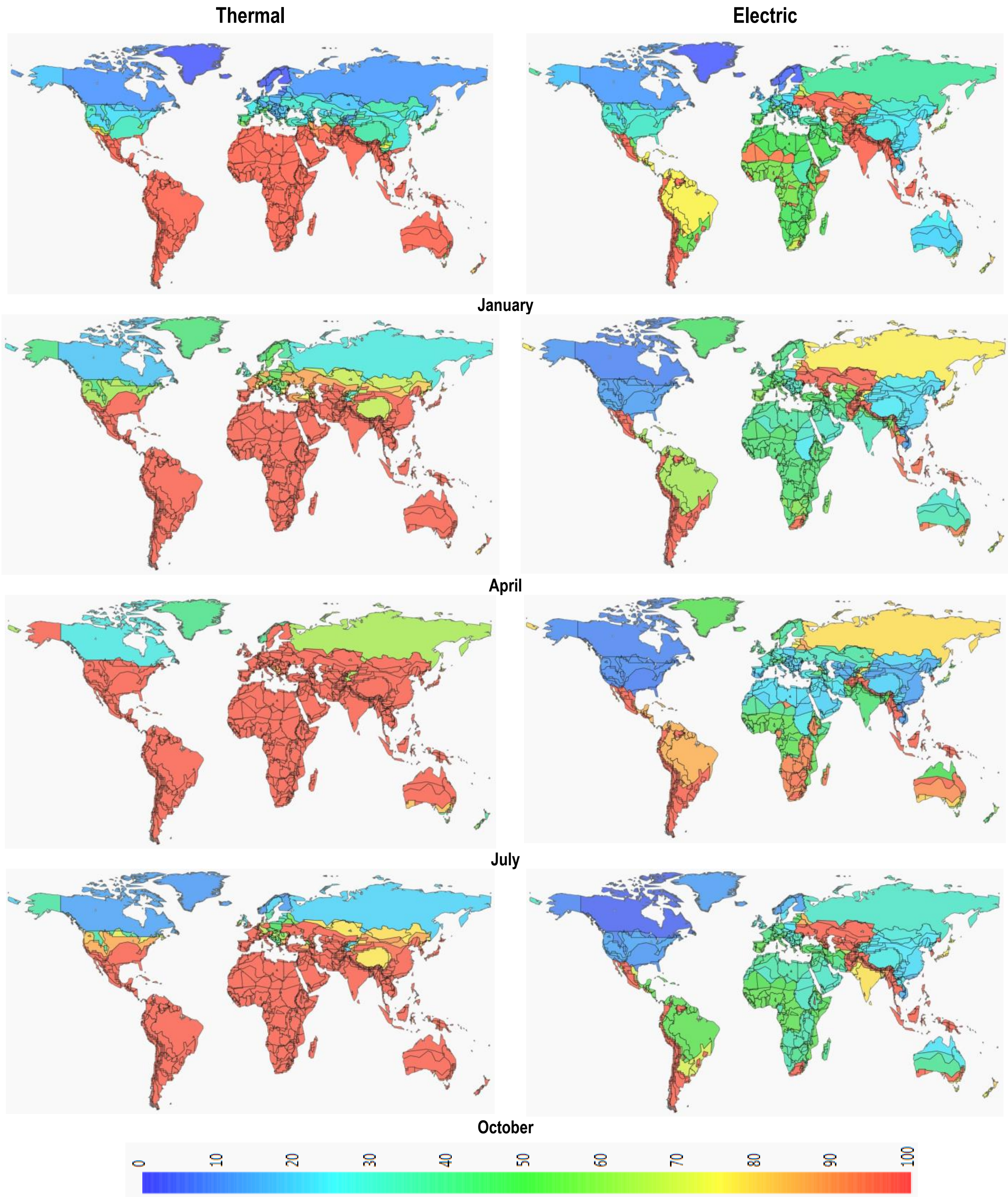


Figure 71. Potential for solar energy to cover building energy needs in 2050 under Deep scenario for multifamily buildings

*Note*: the legend shows the share of energy use, which can be covered by solar energy production

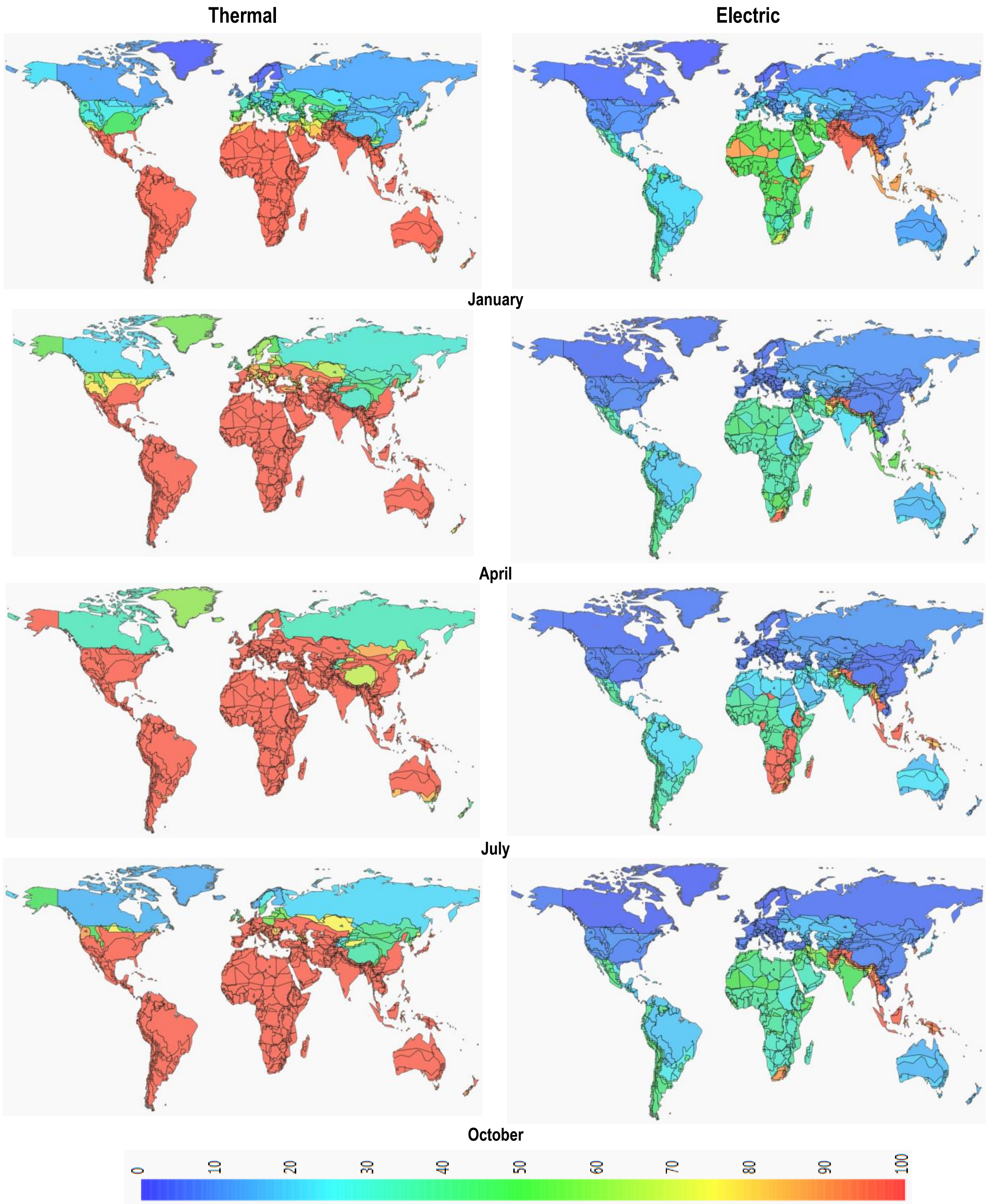



Figure 72. Potential for solar energy to cover building energy needs in 2050 under Deep scenario for office buildings

*Note*: the legend shows the share of energy use, which can be covered by solar energy production

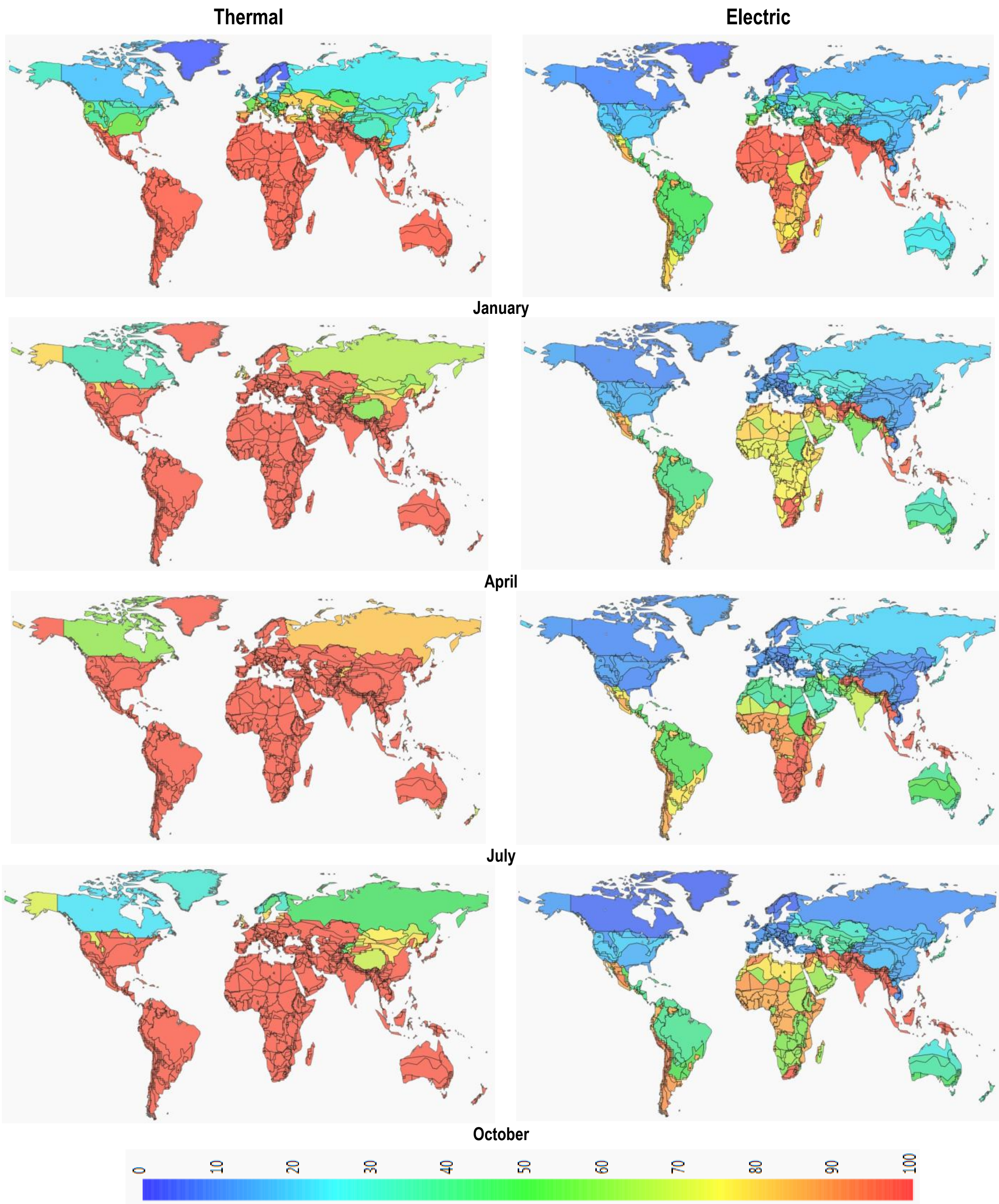
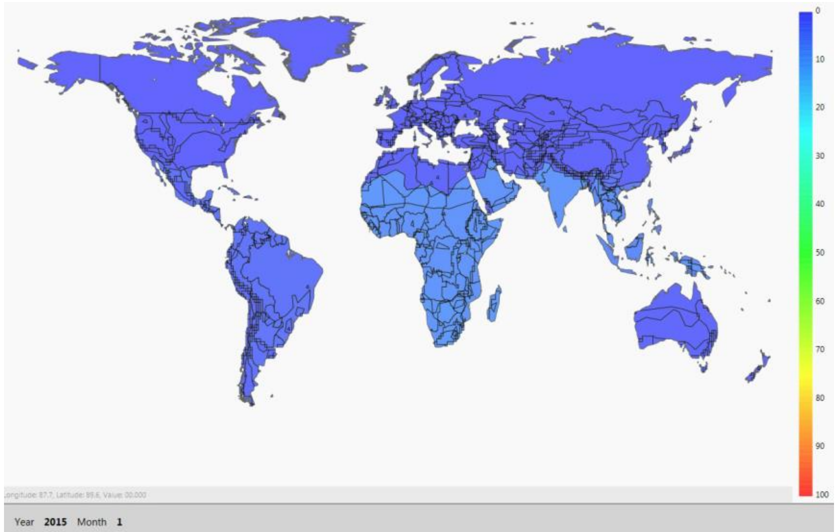
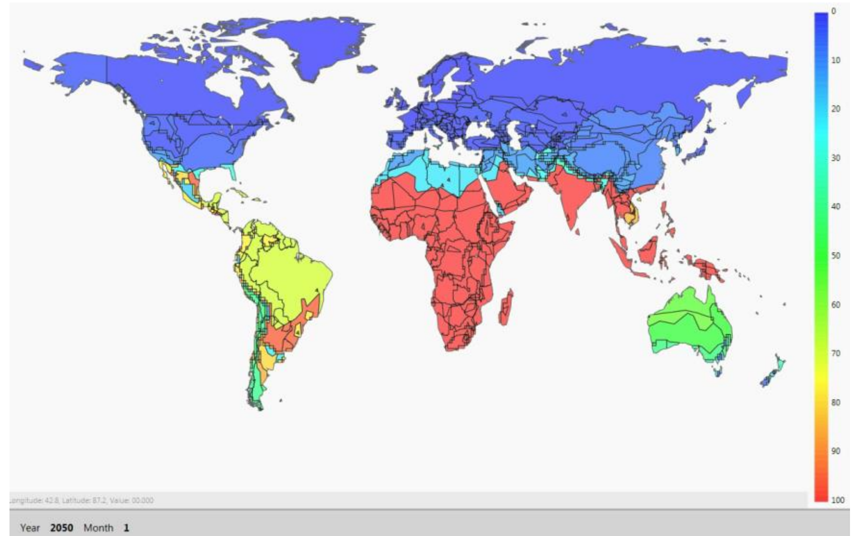



Figure 73. Potential for solar energy to cover building energy needs in 2050 under Deep scenario for educational buildings

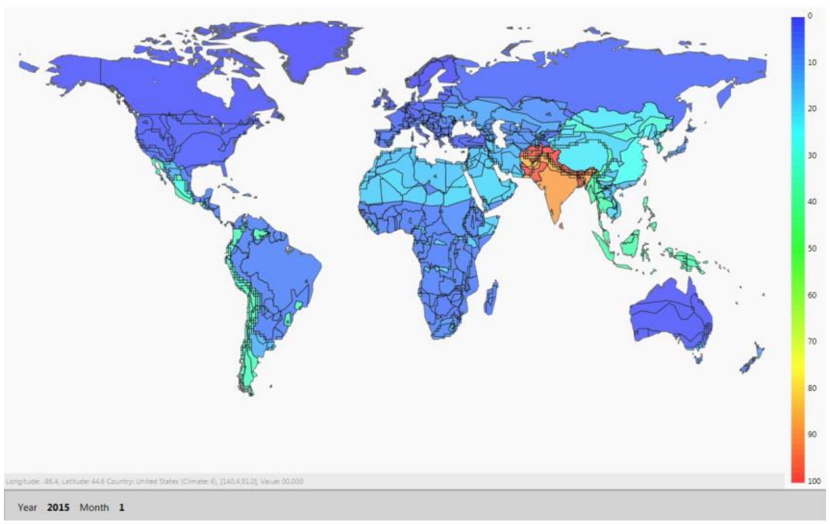
*Note*: the legend shows the share of energy use, which can be covered by solar energy production



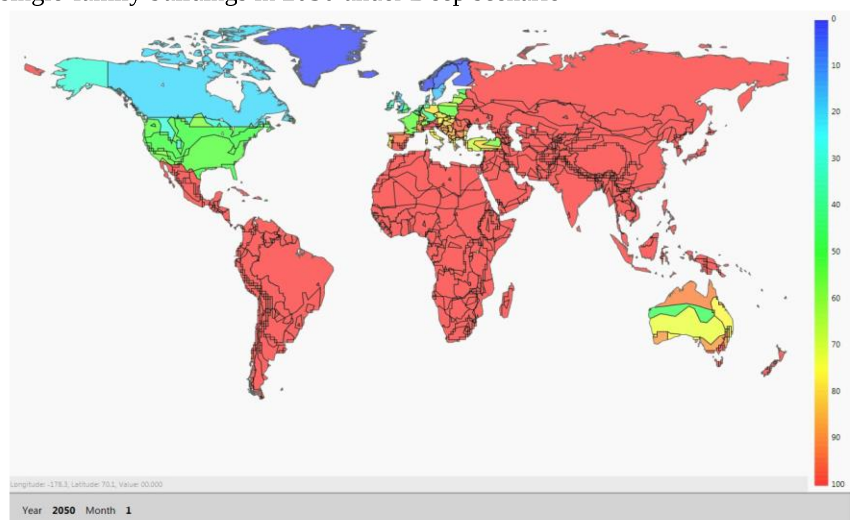
Video 1. Potential for solar thermal energy to cover thermal energy needs in single-family buildings in 2015 under Deep scenario



Video 2. Potential for solar thermal energy to cover thermal energy needs in single-family buildings in 2050 under Deep scenario



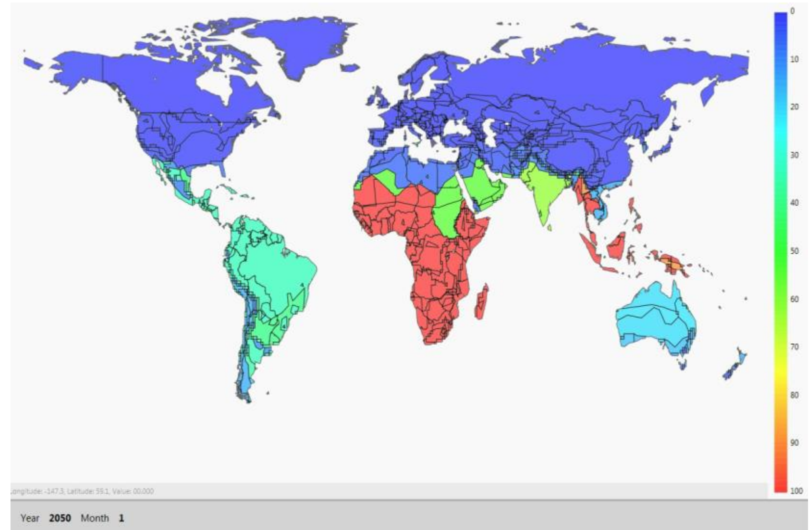
Video 3. Potential for solar electric energy to cover electric energy needs in single-family buildings in 2015 under Deep scenario



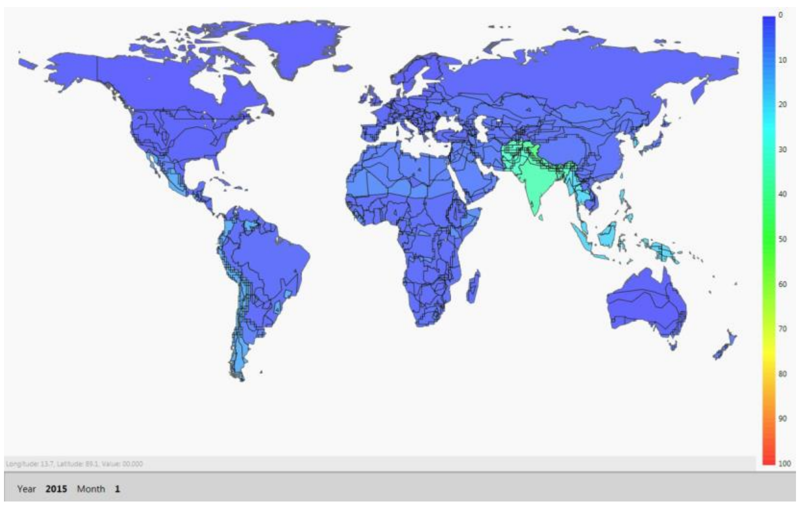
Video 4. Potential for solar electric energy to cover electric energy needs in single-family buildings in 2050 under Deep scenario

*Note*: the legend shows the share of energy use, which can be covered by solar energy production

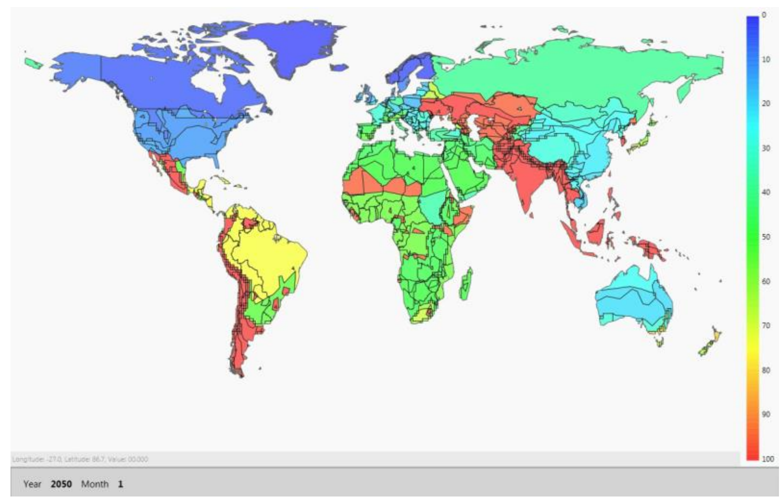

Video 5. Potential for solar thermal energy to cover thermal energy needs in multifamily buildings in 2015 under Deep scenario




Video 6. Potential for solar thermal energy to cover thermal energy needs in multifamily buildings in 2050 under Deep scenario



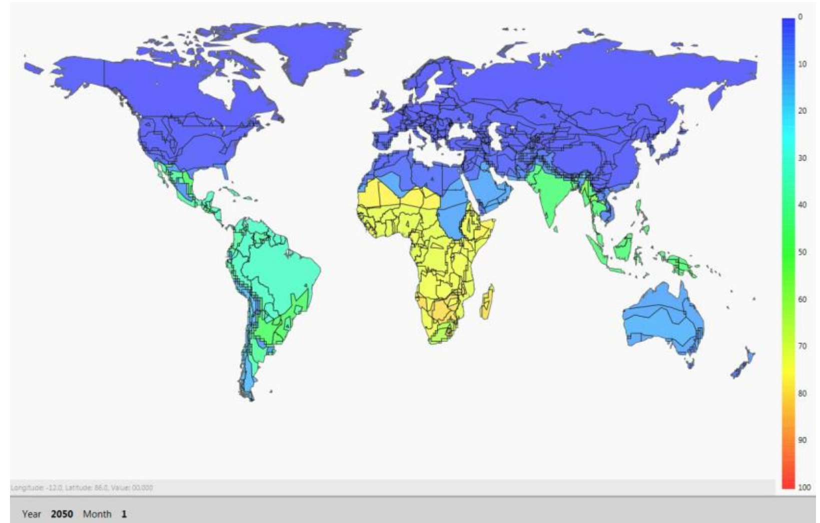

Video 7 Potential for solar electric energy to cover electric energy needs in multifamily buildings in 2015 under Deep scenario



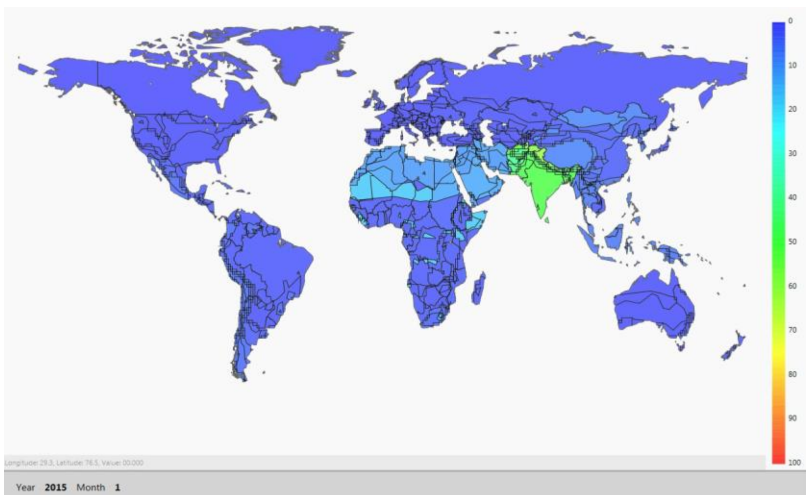

Video 8. Potential for solar electric energy to cover electric energy needs in multifamily buildings in 2050 under Deep scenario

*Note*: the legend shows the share of energy use, which can be covered by solar energy production

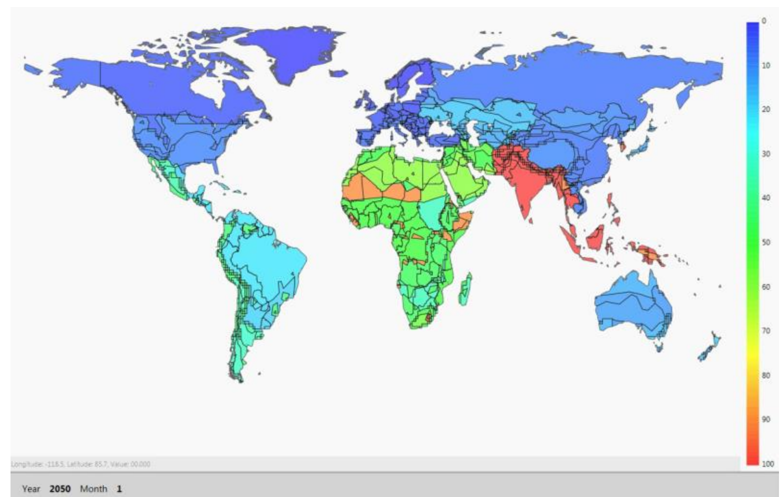

Video 9. Potential for solar thermal energy to cover thermal energy needs in office buildings in 2015 under Deep scenario




Video 10. Potential for solar thermal energy to cover thermal energy needs in office buildings in 2050 under Deep scenario

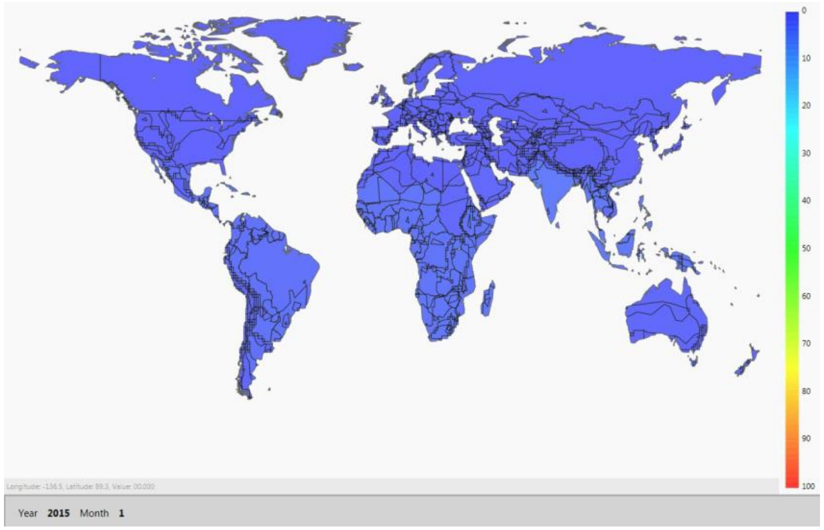



Video 11 Potential for solar electric energy to cover electric energy needs in office buildings in 2015 under Deep scenario

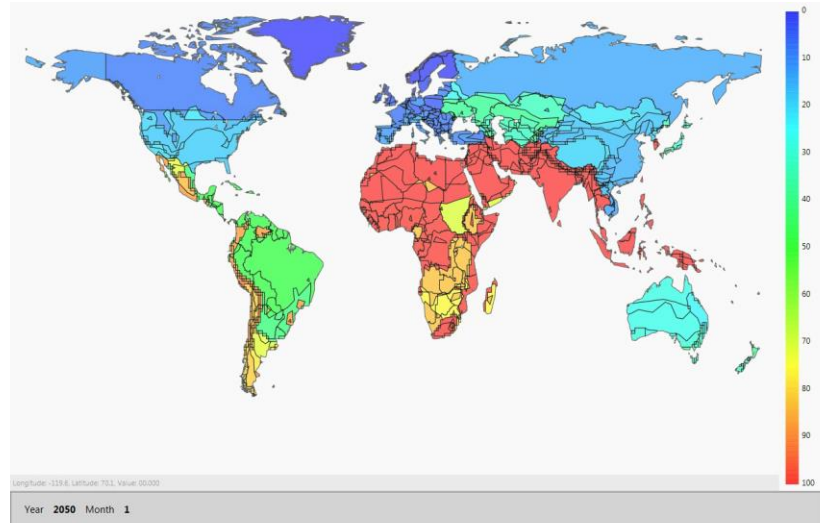



Video 12. Potential for solar electric energy to cover electric energy needs in office buildings in 2050 under Deep scenario

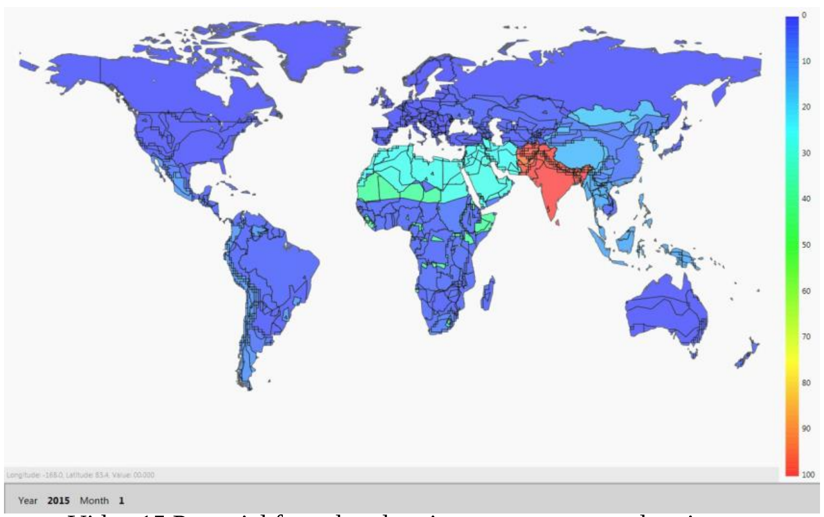
*Note*: the legend shows the share of energy use, which can be covered by solar energy production



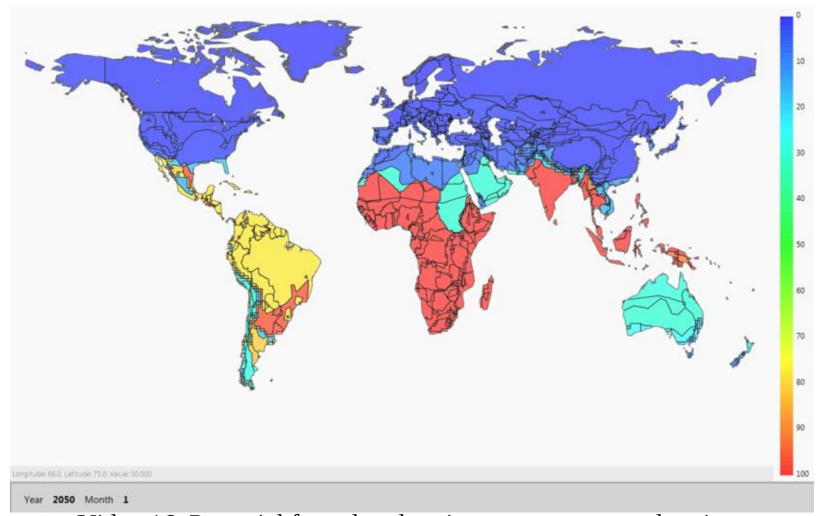

Video 13. Potential for solar thermal energy to cover thermal energy needs in educational buildings in 2015 under Deep scenario




Video 14. Potential for solar thermal energy to cover thermal energy needs in educational buildings in 2050 under Deep scenario




Video 15 Potential for solar electric energy to cover electric energy needs in educational buildings in 2015 under Deep scenario




Video 16. Potential for solar electric energy to cover electric energy needs in educational buildings in 2050 under Deep scenario

*Note*: the legend shows the share of energy use, which can be covered by solar energy production

# IX CHAPTER. CONCLUSION

This final chapter aims at providing a concise summary of the dissertation and important concluding remarks. It is structured around four topics: (1) overview of the dissertation and its key findings; (2) discussion of the results; (3) implication of the research for policy development; and (4) directions for further research. Each of these topics is discussed in more detail below.

## IX.1 Overview of the dissertation and its key findings

As climate change and natural resource depletion are among the most acute global environmental problems of the modern society, technological and policy advancements in these fields are becoming more and more crucial and urgent. Building sector, as the sector, which is responsible for more than one third of global energy demand and related GHG emissions and offers large and cost-effective potential for energy savings (IPCC 2007), has become one of the cornerstones of the national and international sustainable policy agendas.

The scenario analysis commenced in 2007 for Global Energy Assessment Ürge-Vorsatz et al. (2012), extended and improved in 2011-2012 by the research team of Center for Climate Change and Sustainable Energy Policy (3CSEP), including the author of this dissertation, has shown that by 2050 about one third of global thermal energy use can be reduced in relation to 2005 if current energy efficiency best-practices are implemented worldwide (i.e. under 'Deep' scenario). Figure 74 demonstrates results for global final thermal energy use under three scenarios from 3CSEP-HEB model (see Section V.1.1).

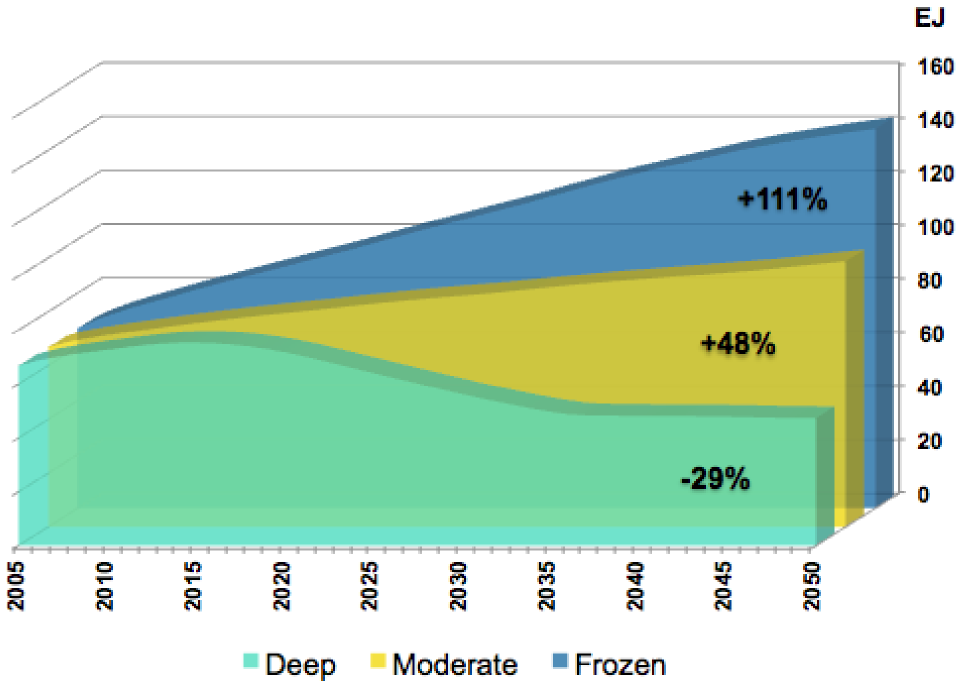


Figure 74. Global final thermal energy use under three scenarios

Source: Urge-Vorsatz, Petrichenko, et al. (2012)

This dissertation brings the analysis of sustainable energy potential in buildings to the next level with the goal to explore how much of this significantly reduced building energy use can be covered by solar energy produced on building site and, therefore, estimate the maximum possible potential for solar-supplied net-zero energy buildings on the global and regional scales (see Section I.2).

In this dissertation net-zero energy building is understood as a residential or commercial building with greatly reduced energy needs through energy efficiency improvements, such that the balance of energy needs can be supplied with renewable energy. There are several important aspects related to NZEBs, which have been discussed in Section II.2:

- Indicator of the balance
- Period of the balance

- Purpose of energy use
- Connection with the energy infrastructure
- Renewable energy supply
- Energy efficiency requirements
- Building type

In this dissertation final energy use for both supply and demand side has been chosen as the indicator of balance. All the results have been obtained on a monthly basis in order to account for the variation in energy needs and solar energy potential across the months and seasons. Presented analysis takes into account the following energy end-uses on the demand side: space heating, space cooling, water heating, lighting and appliances. On the solar supply side it is assumed that solar heat is used for space heating and water heating, while solar electricity - for the remaining end-uses mentioned above. It is assumed that buildings are connected to the electricity grid. As for renewable energy supply the main focus is made on solar energy and presented analysis does not include other renewable energy sources. Energy efficiency requirements for buildings are considered in the analysis for space heating, space cooling and water heating. Potential to achieve NZE goal is discussed for different building types.

In order to achieve the research goal noted above a sophisticated model has been developed, which in this dissertation is called Building Integrated Solar Energy (BISE) model. This model allows for estimating separately solar thermal and solar electric energy output, which can be potentially produced by hybrid PV/T solar technologies. PV/T system is a solar technology, which combines a photovoltaic panel and solar thermal components and is able to produce both solar electricity and heat. Key advantages of this type of solar technologies are that it eliminates the necessity to mount two separate systems on the same roof and offers higher combined efficiency of the system than in case of two independent systems.

For the estimation of solar energy output a sophisticated calculating algorithm has been elaborated based on the approaches and parameters described in the literature for estimating the performance of individual solar systems (see Section V.2).

For the demand side results on energy use for space heating and cooling, as well as water heating were taken (with certain modifications) from the Deep Efficiency scenario of 3CSEP-HEB model (see Section VII.2), while energy use for lighting and appliances – from Business-as-usual scenario of BUENAS model (see Section VII.3). Analysis of the results presented in Chapter VIII is based on the comparison between monthly (and sometimes daily) energy use and potential solar energy supply in buildings separately for thermal and electrical energy for different regions, climate zones and building types.

Key findings from the analysis of the results presented in this dissertation can be summarized in the following way:

**KEY FINDINGS**:

- There is a significant potential to cover building energy needs with solar energy, although solely solar energy is not sufficient for ensuring NZE building performance under a number of circumstances (e.g. high-rise buildings, climates with high heating or cooling demand, etc.)
- Low-rise buildings (e.g. single-family buildings) demonstrate higher potential for achieving NZE goal than high-rise ones (e.g. office buildings)
- Results for heating-dominated climates demonstrate need for supplementary heating, while in cooling-dominated climates the problem of excessive solar heat might be significant
- Developing countries have a higher potential for NZEBs supplied totally by solar energy, due to abundance of solar energy resources. These countries have the opportunity for 'solar leapfrogging'

- NZEBs targets and definitions should be adjusted based on the climate and building type
- Energy efficiency of all building systems is crucial for sustainable achievement of NZEB targets; thus, respective requirements should be an essential part of any NZEB definition
- Achievement of the NZEB goal is possible if very strict building regulations are combined with strong appliance standards and rigorous policy measures for energy efficient lighting, especially in C&P buildings

Analysis of the results is structured around ten key messages, which have been concluded from this comparison:

1. Accurate energy balance calculation requires a shorter timescale
2. Low-rise buildings have higher potential to achieve NZE goal
3. Energy efficiency plays a crucial role in NZEBs
4. Moderate climates offer higher potential for NZEBs
5. Realisation of solar potential in buildings in developing countries allows for their ‘leapfrogging’ to a more sustainable path
6. Short-term energy storage can increase potential for NZEBs
7. Efficient appliances and lighting are crucial for NZEBs: sensitivity analysis for respective energy intensities
8. Larger unshaded roof areas increase potential solar energy supply: sensitivity analysis for roof shading factors
9. Smaller roof areas available for solar technologies may significantly reduce solar energy potential: sensitivity analysis for roof facility factors

10. A number of building types and climate zones demonstrate high potential for solar-supplied NZEBs

Comparison of regional results for thermal and electric energy (use vs solar supply) for the annual and monthly scales (see Section 0) has clearly shown that analysis of the energy balance for each month not only beneficial for obtaining more robust results, but also crucial for NZEBs design. In a number of cases buildings, which can achieve a net-zero energy balance on the annual basis, may not reach this goal for certain months. Annual comparison in its nature automatically incorporates the assumption for the possibility of seasonal storage of solar energy (as solar energy produced across all the months is summarized and is compared to the annual energy use), which is rarely used in practice due to high costs and limited efficiency and is not considered in BISE model. Analysis of the energy balance on a monthly basis gives better understanding of seasonal and monthly energy use and solar energy supply profiles and variations in response to the changing climatic conditions. This understanding is very important for building design, choice of technology mix and sizing of solar systems.

The next message demonstrates the importance to take into account building type when analyzing potential of a building to achieve NZE balance. Section VIII.2 has presented the results separately for thermal and electric energy use and solar energy output for single-family, multifamily and commercial & public buildings, as well as for different commercial & public building sub-categories. The results have clearly shown that single-family and other low-rise buildings provide the greatest opportunity to achieve NZE goal and even move towards energy positive buildings in some locations. High-rise buildings (e.g. typically multifamily buildings, offices, etc.) have much more limited available roof area for solar technologies installations in relation to the floor area, from which energy use is taking place. Such a building typology often results in insufficiency of solar energy supply to cover a larger portion of building energy needs. Moreover, different building types have different patterns for building energy use. For example, in commercial buildings the share of lighting is much larger than in residential buildings, in which appliances usually play a much more significant role. Another important point is that energy intensities for lighting and appliances are coming from the business-as-usual scenario of BUENAS model and might be quite high in 2050 in a number of regions. This, therefore, aggravates the possibility to cover electrical energy needs in buildings solely with solar energy in a number of locations, but most drastically – in developed regions.

Necessity to reduce energy use in buildings through energy efficiency measures is often included in the definitions and important requirements for NZEBs (see Sections II.1 and II.2). Results presented in Section VIII.3 aim at demonstrating the difference in the potential to achieve NZE level in buildings in 2050 under Deep and Moderate scenarios for building thermal energy use. Deep scenario provides the estimations for thermal energy use if ambitious energy efficient measures are implemented for space heating, cooling and water heating, while Moderate scenario was designed to reflect the level of thermal energy use if current modest technological and policy developments are continued by 2050 in each region. The results of the comparison between scenarios show that very high building energy performance is needed in order to achieve net-zero energy goal. Moderate efforts in building energy use by the mid-century significantly lower the share of energy use, which can be covered by solar energy supply in a number of regions and building types, as energy use for space heating, cooling and water heating is notably larger under Moderate scenario than under Deep one. It is particularly critical in developed regions, which have relatively lower availability of solar resources and higher energy requirements for space heating. The major difference between scenarios for electric energy use can be seen in cooling-dominated climates and during summer months.

Besides building types it is very important to take into account climate conditions, in which buildings are located. Comparison of the monthly energy balances, presented in Section VIII.4 for different regions and selected climate zones, has illustrated that different climate conditions influence both energy use and potential solar thermal and electric energy output. It is worth to note that this dissertation uses the climate typology purposefully designed by the author for the research related to building energy use and its interdependence with climatic conditions. The results presented for a number of climate zones demonstrate that in heating-dominated climates, especially with high heating demand the opportunity to cover thermal energy needs only with solar thermal energy supply is very limited, at least during the coldest months. Climate zones and regions, where heating demand is lower demonstrate higher potential for full solar coverage of thermal energy needs. In developing countries with abundance of solar resources in a number of climate zones the problem of excess solar heat is likely to occur. As for electric energy use and potential solar electricity production, climate zones with high cooling demand demonstrate more difficulties in reaching NZE balance. Although cooling energy use in 2050 in a number of regions, climate zones and months has relatively small share in total electricity demand, during hot period of the year increased cooling demand in cooling-requiring climates often makes solar electricity output insufficient to cover all building electricity needs.

Other important results demonstrate the possibility for developing countries to leapfrog toward low-energy and low-carbon buildings through realization of building-integrated solar energy potential. It is especially important, as developing countries are expected to grow rapidly both in terms of floor area and energy use during the next several decades. Therefore, energy efficiency improvements and utilization of renewable energy in buildings are crucial. Results presented in Section VIII.5 for selected developing regions demonstrate that a number of building types (e.g. single-family and educational buildings) by 2050 (and in a number of cases already by 2030) have a significant technical potential to cover all building energy needs solely with solar energy produced on the building site.

Analysis of the results modeled for every day of January 2050 (see Section VIII.6) have demonstrated that in low- or medium-rise buildings short-term storage can play an important role for reducing or eliminating need for supplementary (to solar) space heating systems. Daily solar energy output to a large extent is determined by the amount of solar radiation available for the roof-top systems. Therefore, storing solar energy, which was not consumed during some days in order to supply the building during the days, when amount of generated solar energy is not sufficient to cover building energy needs, can be very beneficial for improving monthly energy balance towards NZE. In high-rise buildings (e.g. multifamily, office, in some regions educational and hospital buildings), however, solar energy supply cannot cover a large portion of building energy use during most of the days in January and, therefore, short-term energy storage will not considerably assist these buildings in getting closer to NZE status.

In order to see the impact of several important parameters, which have high level of uncertainty for the assumptions, the sensitivity analysis was conducted, results for which are presented in Sections VIII.7 - VIII.9, which allowed for concluding the following critical messages:

- Energy efficient appliances and lighting play an important role in the building energy balance
- Variation of the energy intensities for appliances play an important role in the energy balance of residential buildings

- Variation of the energy intensities for lighting has a notable impact on the total electrical energy use in office (and other commercial & public) buildings
- Increase in roof areas available for solar systems installations through variations in shading and facility factors can be beneficial for high-rise buildings, which are characterized by small roof areas in relation to floor areas, as such increase will allow for larger solar fraction in these buildings

The global picture presented in Section VIII.10 has demonstrate potential to cover thermal and electric energy needs with solar energy on the global scale by means of colorful maps and videos. Two maps (separately for thermal and electric energy) for single-family buildings are presented in Figure 75 as examples. The maps show significant potential for this building type to cover all building energy needs with the solar energy produced on site. More high-rise building types (e.g. offices), however, demonstrate much lower potential in a number of location, especially for the electric energy balance. According to the results, for such building types solar energy produced on the building's roof is not sufficient to satisfy all electricity needs.

In order to realize this great potential introduction and enforcement of effective policy packages are needed. Such a package should include stringent building performance regulations, as well as appliances standards and measures for energy efficient lighting.

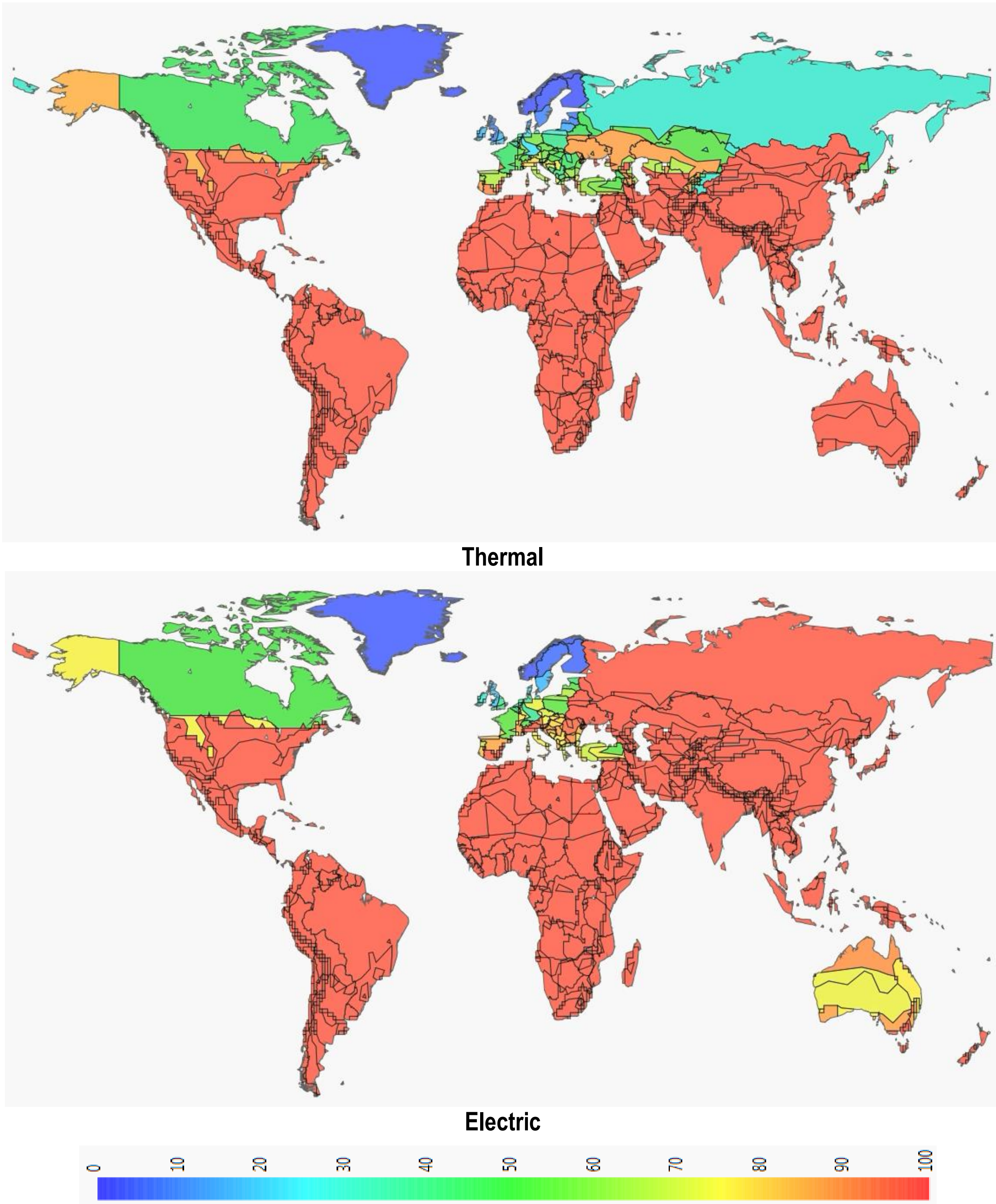



Figure 75. Potential for solar energy to cover building energy needs in January 2050 under Deep scenario for single-family buildings

*Note*: the legend shows the share of energy use, which can be covered by solar energy production

In the beginning of this dissertation (see Section I.2) a number of research questions have been set, which now can be briefly answered based on the discussed results (see Table 33).

Table 33. Brief answers to the research questions based on the research results

| Research question | Brief answer based on the results |
|---|---|
| *In what regions and climate zones are NZEBs technically feasible, according to the local climatic conditions and availability of natural resources?* | The best answer to this question can be given by means of maps and videos presented in Section VIII.10 and XV.1 in Annex E. A general trend is that the greatest potential can be observed in developing regions located in the Southern Hemisphere and in the climate zones with moderate or low heating and cooling demand. Potential to cover all thermal energy needs with solar energy is limited in heating-dominated climates. Potential to meet all electrical energy needs with solar supply is limited in cooling-dominated climates and developed regions due to high energy intensities for appliances and lighting assumed under BAU scenario |
| *How does the potential for solar NZEBs vary across different building types?* | Typically low-rise building types (e.g. single-family and retail buildings) demonstrate the greatest potential for solar-supplied NZEBs. On contrary, high-rise buildings, having smaller roof area available for solar systems in relation to floor area, from which energy use is taking place, are not able to produce sufficient amount of solar energy. It is particularly true for most of commercial & public building sub-categories, which demonstrate notable electricity demand for lighting and in a number of months – for cooling |
| *How much building energy needs can be met by 2050 with solar energy produced by building-integrated solar energy technologies?* | In the Northern hemisphere solar energy is not sufficient to cover thermal energy use during wintertime in all building types due to high heating load. In the Southern hemisphere potential solar thermal energy supply usually can cover most of the related energy needs throughout the year. As for solar electricity, the potential to cover buildings' electricity demand is much more limited. Full coverage is possible in single-family buildings during wintertime in a number of locations with exception for some developed regions with high energy needs for appliances. During the summer increased cooling loads decrease potential solar fraction even further. In other building types this fraction varies from 5% to 100% depending on the location and building type. |
| *What are the implications of the research for policy development to drive the building sector toward net-zero energy goals?* | It is essential to take into account building type and climate conditions, when setting the NZE goals. It is likely that strict building regulations, such as building codes, which can tackle only energy end-uses related to the building shell (space heating, cooling, hot water), are going to be insufficient for achieving NZEBs targets and, therefore, have to be combined with ambitious appliances standards, incentive policies for efficient lighting, information and educational campaigns in order to explain how NZEBs should be operated. It might also be considered not to include appliances into NZEB definition. |



## IX.2 Discussion of the results

The results of the research presented in this dissertation have demonstrated that a great technical potential for solar-supplied net-zero energy buildings exist on the global and regional scales. In a number of regions and building types it possible to achieve net- or nearly zero level of building energy performance especially for low- and medium-rise buildings. However, it has to be emphasized that it was the key research goal to estimate maximum achievable technical potential and not to attempt forecasting possible future or estimating the likelihood of different scenarios.

According to Voivontas et al. (1998) cited in Mondal and Denich (2010), technical potential for renewable energy sources can be defined as “the amount of energy that can be exploited using existing technologies and thus depends on the time point of assessment”. From this definition it follows that technical potential includes neither evaluation of the probability for this potential’s realization nor the costs of such realization. The latter would require evaluation of economic potential, which refers to “the amount of potential energy that is economically viable by currently given technologies” (Mondal and Denich 2010). This dissertation does not include estimation of economic potential due to time and resource constraints, however, it acknowledges it as an important direction for further research (see Section IX.4). This dissertation does not present a picture of the future, which will happen by 2050, but rather discusses what can be achieved with energy efficiency measures and advanced solar energy technologies in buildings.

Traditionally discussion of the results aims at comparing the original research results with the ones available from other studies, publications and reports. In case of this dissertation such an opportunity is quite limited as to the author’s best knowledge such an estimation of the technical solar energy potential from hybrid solar energy technologies on the global scale is a pioneer in its nature.

Most of the literature, which has been found, focuses on evaluating the potential from PV technologies. However, the attempts to provide estimations for the whole world are quite scarce and the sources usually narrow down the geographical scope to much smaller areas. For example, Wiese et al. (2010) estimated technical potential of roof-tops for Austin Energy's service area at the level of 3.3 million MWh per year. Leitelt (2010) present results for Chapel Hill in the US, where potential annual energy output from PVs installed at all available roof tops is 107,484 MWh. Castro et al. (2005) developed several scenarios for estimating potential solar electricity output from PV mounted on available roof areas in South region of the Iberian peninsula in Spain. According to the authors, by 2020 this region could produce 529 TJ of solar electricity under Moderate scenario, 937 TJ – under Normal scenario and 1875 TJ – under Ambitious scenario.

A few studies have explored the potential of solar water heating systems. Pillai and Banerjee (2007) calculated that the technical potential of solar water heating systems for the 'synthetic area' of Puna in India is 0.39 million lpd, which is equivalent to 6300 $m^2$ of collector area. Using 8005 municipalities of Spain as a geographical scope Izquierdo et al. (2011) estimated that roof-top solar water heating systems can supply1662 ktoe/yr of primary energy and 30.5 TWh/yr of total energy. The authors also estimated potential electricity output from roof-top PVs at the level of 10 TWh/yr.

Although these studies undoubtedly present important scientific contributions to the field of knowledge, their results cannot be directly compared to the ones presented in this dissertation, as BISE model provides estimations of the solar potential for the whole world and large geographical regions. The only study with a comparable geographical coverage, which could have been found, is Hoogwijk (2004). Although the author estimates only technical potential of PV electricity (and not solar thermal), the results can be compared to the ones estimated by BISE model for the solar electrical output. The author provides the results for 17 large regions, which to some extent can be harmonized with 11 regions covered by BISE model through certain aggregation. Moreover, Hoogwijk offers the estimates only for the base year (2001), while BISE model presumes a transition period for hypothetical proliferation of solar systems in the building sector between 2014 and 2025. Therefore, BISE model does not have the estimations for the solar potential in the base year. For the purpose of comparison technical potential for solar electricity from BISE model has been estimated for the base year (2005) by calculating aggregated solar electric output per square meter of available roof area in 2050 and multiplying this 'intensity' by the available roof area in 2005 in each region. Although the base years are different in the two models, the author believes that the results are still comparable.

The results of this comparison by region can be seen in Figure 76. This figure shows that the results of the two potential's assessments are at the same level of magnitude. Regions like Latin America, Former Soviet Union, South East Asia and Eastern Europe demonstrate quite similar results between two models. However, there are regions, in which results differ substantially (e.g. East Asia vs CPA, North+West+East+South Africa vs AFR, Europe OECD vs WEU, etc). In some cases it can be explained by the fact that regions considered in the two models include different set of countries. However, a more significant impact is likely to be made by the difference in the approach to estimating available roof areas for solar systems installation. In more details the approach used in Hoogwijk (2004) was discussed in Section VI.1.2 (page 161). This approach very much depends on the data for GDP per capita and Hoogwijk herself acknowledges that results for some regions (e.g. Japan) might be distorted by such an approach, which also influences the results of estimation for the decentralized PV potential. Moreover, the study assumes a fixed PV efficiency, while BISE model is designed to take into account hourly, daily and monthly climatic variations in estimating the electrical efficiency of the solar systems for a given location of the globe.

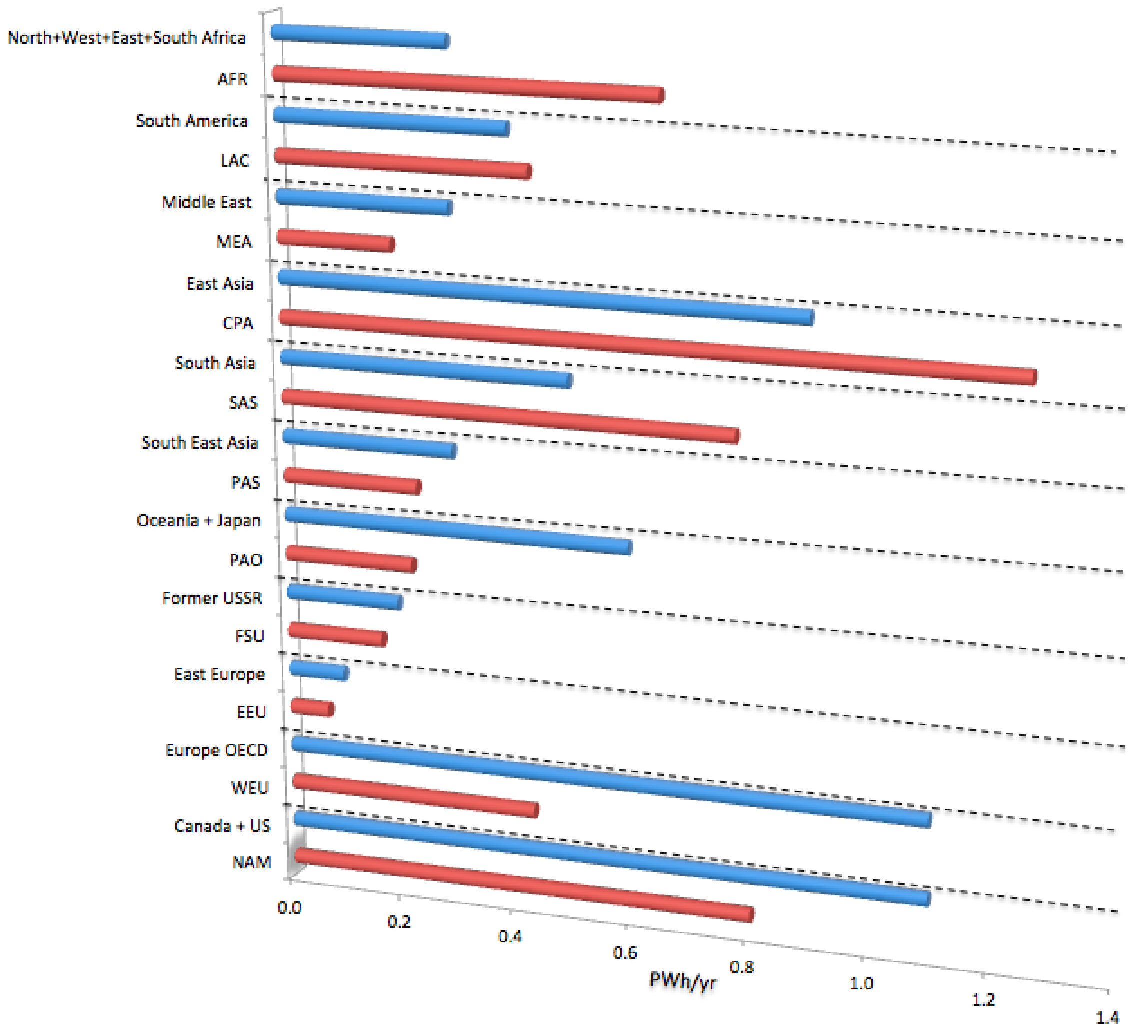



Figure 76. Results on the technical potential for solar electricity produced on building site in the base year: comparison between BISE model and estimations from Hoogwijk (2004).

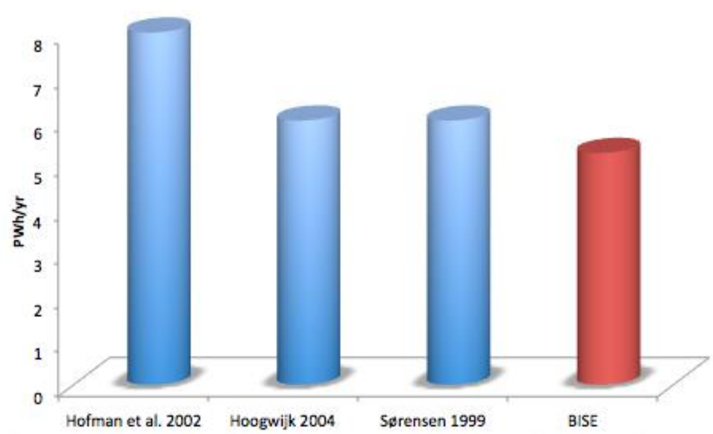



Figure 77. Comparison of the global technical potential for the annual PV electricity production between BISE model and three other studies

On the global scale Hoogwijk estimates the technical potential for electricity produced by decentralized grid-connected on-site PV systems at the level of 6 PWh/yr. The author also compares her results to other two similar global estimates presented in Sørensen (1999) and Hofman et al. (2002) . Comparison of three studies to BISE model is presented in Figure 77.

As it can be seen in Figure 77 Hoogwijk and Sørensen present very similar estimates, which can be explained by a number of similarities in the approach and assumptions. Hofman et.al. demonstrate the highest value for the potential solar electricity production among all four results mainly due to different approach to estimating the roof area and assumptions for PV efficiency. (for more details see Hoogwijk 2004, page 178). In spite of having significantly different methodological approach from all three outlined studies BISE model presents very similar results to the ones provided in Hoogwijk (2004) and Sørensen (1999). BISE's results are slightly lower, which can be explained by rather conservative estimations for available roof areas and more detailed calculation of electric efficiency, which varies depending on weather conditions.

One of the most important conclusions made in this dissertation is that developed and developing regions have notably different potentials to achieve high solar fractions in buildings. Developing countries demonstrate larger potential to cover building energy needs with solar than developed ones across building types. It is a logical conclusion, which becomes clear if we compare the result on availability of solar radiation with energy consumption per capita and per square meter in different regions presented in the sources other than this dissertation.

Figure 78 shows the amount of global solar irradiation received by the surfaces on the ground. It can be seen from the picture that regions in the Southern Hemisphere have the highest availability of solar resources, most of which (except for Australia, New Zealand and Southern part of US) are developing countries.

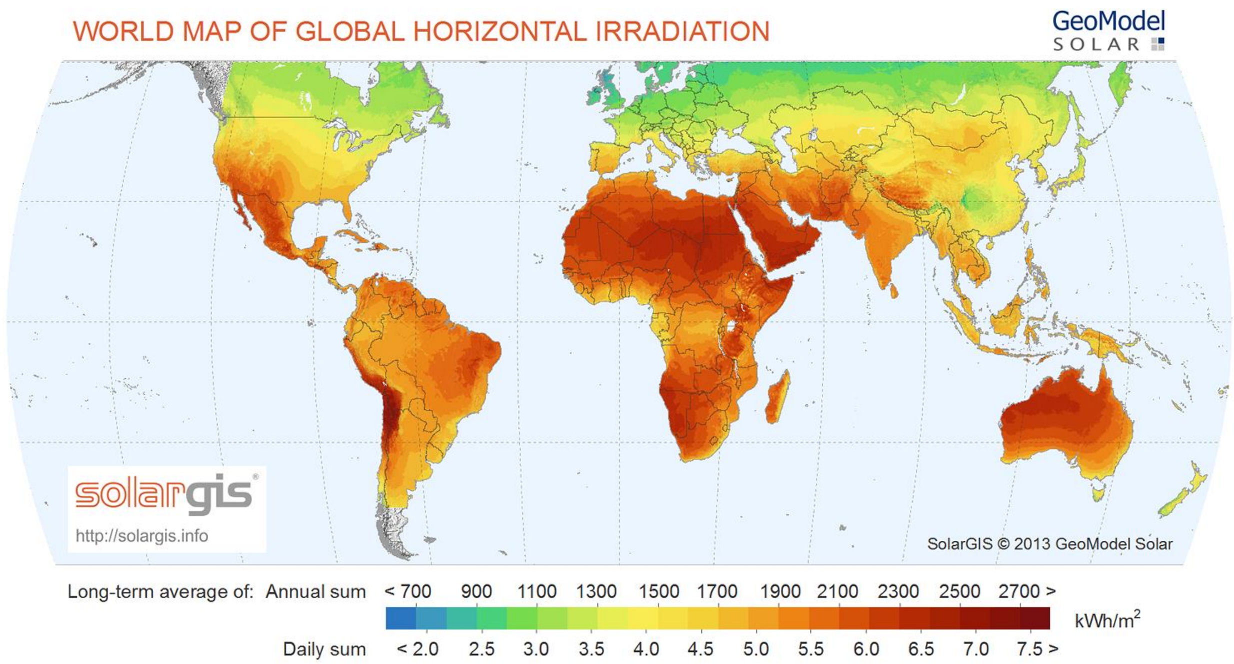



Figure 78. World map of global horizontal irradiation

Source: SolarGIS (2013)

On the other hand, developed regions typically have higher level of energy consumption than developing ones due to higher energy demand for space heating and level of energy services. Figure 79 shows that energy consumption per capita in both residential and commercial building is 1.5-3 times higher in developed regions in comparison to the developing ones.

Figure 80 illustrates final energy intensities for space heating and cooling in three building types. It is very clear that specific energy consumption in such regions as North America, Western and Eastern Europe and Former Soviet Union demonstrate is notably higher than in other regions.

Combination of high solar irradiation with relatively low energy consumption in developing regions increases technical feasibility of net-zero energy buildings supplied with solar energy produced on the building site technically in these locations, which is often higher than in developed ones as it was demonstrated by the results of BISE model.

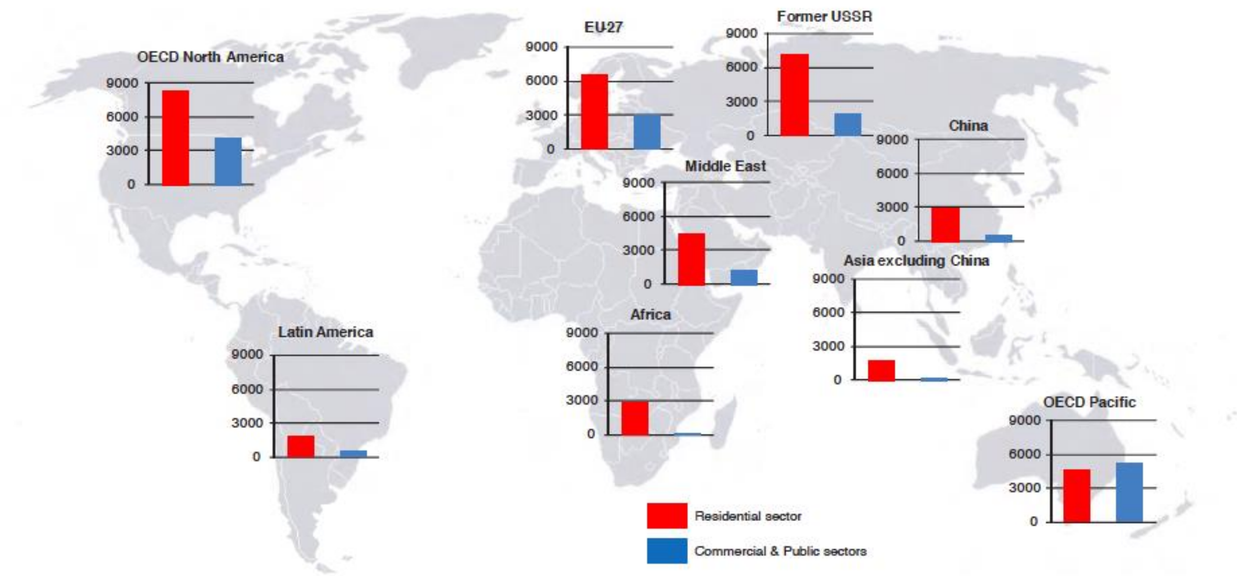



Figure 79. Total annual final energy use in the residential and commercial/public sectors, building energy use per capita by region and building type in 2007 (kWh/capita/yr)

Source: Ürge-Vorsatz et al. (2012)

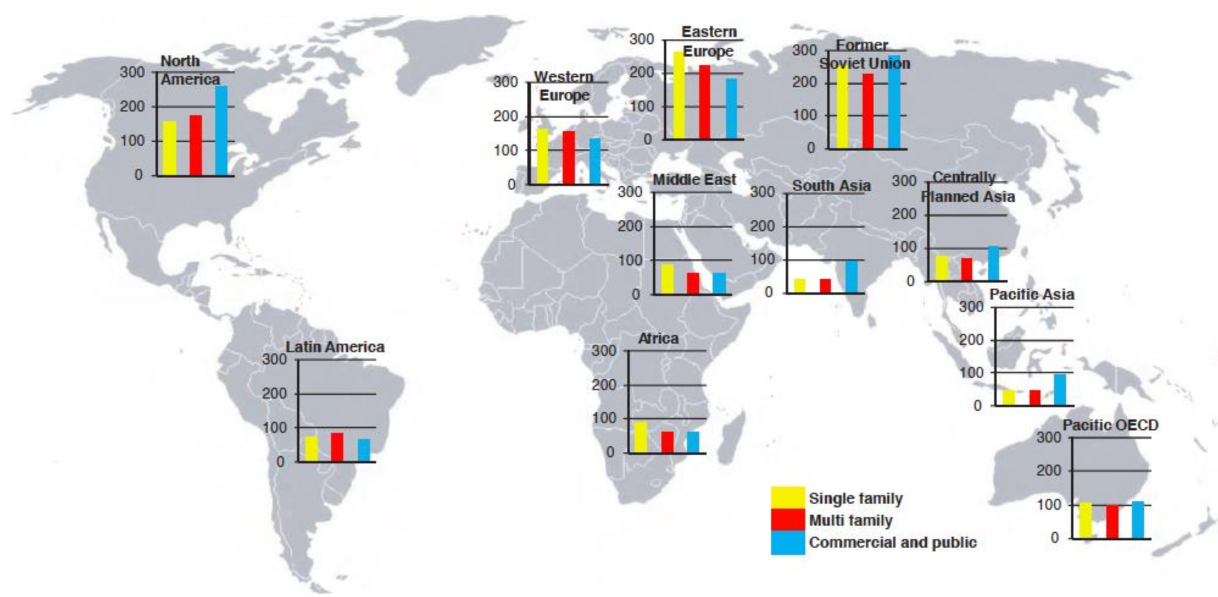



Figure 80. Final heating and cooling specific energy consumption by region and building type in 2005 (kWh/m$^2$/yr)

Source: Ürge-Vorsatz et al. (2012)

## IX.3 Implication of the research for policy development

In the situation when net- and nearly zero energy targets and other related policy efforts are mushrooming in a number of countries, the results of this dissertation provide an important scientific contribution to the developing methodologies, choosing the definition and setting goals for increasing share of NZEBs in national and regional building stocks.

One of the most important policy implications is related to the achievement of the NZEB targets through policy efforts. This dissertation has presented the overview of the maximum achievable technical potential for building-integrated solar technologies. In order to realize this great potential very strong and ambitious policy efforts are needed. As it was pointed out in Section II.1, net-zero energy buildings should combine energy efficiency measures with renewable energy supply. In practice both of these aspects of NZEBs require policy support and development and often may need different policy instruments.

Analysis presented in this dissertation presumes that all new and retrofit buildings have high building energy performance in terms of space heating, space cooling and water heating by 2023 and, therefore, by 2050 most of the buildings are expected to have very efficient building shell. As it is explained in Urge-Vorsatz, Petrichenko, et al. (2012), in order to achieve this, strict well-enforced performance-based building codes and other related regulations, covering both new and retrofit buildings, are required. BISE model also acknowledges that such buildings regulations are crucial, however, are often insufficient for solar-supplied NZEBs. What is needed is an effective policy mix, which would include effective building regulations as described above, strict product standards for appliances and rigorous policy instruments for energy efficient lighting (phasing out inefficient light bulbs, financial incentives for energy efficient ones, etc.) as well as long-term information campaigns and education/training programs about NZEBs and energy efficient technologies. Moreover, it might be necessary to develop special 'user manuals' for the owners of already built NZEBs, where it can be explained in simple words how the building should be operated in a way that the net-zero energy balance is maintained and is not distorted by users' behavior and rebound effect.

This dissertation has clearly demonstrated that the technical potential for solar generation on building site varies across building types. It means that building geometry has to be considered when setting the NZE targets. For example, it might be beneficial to adopt stricter requirements for building energy performance in low-rise buildings, as they have more advantageous geometry for realization of solar energy potential. On the other hand, for high-rise buildings it is often technically not possible to achieve the NZE status solely with solar and, therefore, in those building types other technologies should be used or, for example, some end-uses might be excluded from the NZE requirements.

It is a big question whether appliances and other plug loads should be considered in NZEB methodologies and definitions, as they are not part of the building envelope and are being regulated by different policy instruments than buildings themselves (e.g. building codes – for building shell vs. product standards – for appliances). Moreover, energy use, which occurs in a building from appliances is determined by the users' choices and behavior to high extent, and, therefore, it is much harder to regulate it (i.e. special programs exist to incentivize people to buy energy efficient appliances, but it still remains a matter of a personal choice).

Results of BISE model show that appliances are responsible for a substantial share of electricity use in buildings for residential buildings (see, for example, Figure 65). Therefore, if appliances are excluded from the NZEB definition, the share of electricity use, which could be covered by solar electricity would substantially increase (at least, in residential buildings) and, so will do the chance to achieve NZE goal. It is particular important for multifamily buildings, where usually only small portion of electricity use can be covered by solar energy due to limited floor area in relation to floor area.

Another important policy implication may follow from the message that solar energy potential in buildings differs in various climate zones. For example, in cooling-dominated climates it might be important to provide the incentives for solar cooling and/or PV/T systems with maximized electric efficiency, as the share of electricity in the fuel mix in such locations is typically substantial. In heating-dominated climates it might be essential to promote solar systems together with other technologies, which can provide supplementary heating, where needed. For the areas with very high heating demand it may be solar-powered heat pumps. In the areas, where heating demand is moderate, but solar thermal is insufficient during some months of the year, it might be advisable to combine solar technologies with mobile efficient electric heaters, which can be easily turned off, when not needed. All these technological combinations and options have to be explained to the users through energy consultations, energy audit and information campaigns. Financial support programs might tackle the barrier of the upfront costs, if are well-targeted to a certain group of customers and/or particular technologies (such as the ones mentioned above).

## IX.4 Directions for further research

As it has been pointed out previously this dissertation offers a novel approach to estimation of the maximum achievable technical potential for solar energy produced by building-integrated solar technologies on the global and regional scales. The analysis of the result obtained from BISE model aims at contributing to the policy discussions around the concepts, methodologies and policy instruments related to net-zero energy buildings.

To the author's best knowledge it is the first scientific attempt to assess solar energy (both thermal and electric) potential on the global level and with a high level of methodological details and the link to the discussion of the technical feasibility of NZEBs. However, there is a number of ways, in which the discussion initiated in this dissertation can be developed further. Directions for further research, which the author found the most relevant and important are the following:

- Further research could include assessment of other renewable energy sources, such as wind, geothermal, and sustainable biomass energy
- Potential of other solar technologies can be considered, including not only hybrid PV/T systems, but also separate installations of solar thermal collectors and PV systems (although this would require certain solutions for solving 'battle on the roof' between different types of systems)
- Combinations of different technologies can be explored (e.g. solar-powered heat pump, solar cooling systems, solar collectors + on-site wind turbine, etc.). Application of different technological mixes can be analyzed for different climate zones and building types
- It might be interesting to consider various climate change scenarios in the assessment of the future renewable energy potential
- An important next step would be assessment of economic potential for on-site solar energy and other renewable energy sources utilization
- Calculation algorithm can be further improved by including more options for a user-friendly variation of the parameters, for example, inlet water temperature, reference efficiency of the system, which can change over the time, optical and technical

parameters of the systems. This may provide the opportunity for comparative analysis of the performance of different systems' types

- More detailed calculations can be done on the demand side, which could allow for obtaining daily or even hourly energy loads for different end-uses. It would enable the analysis of daily and hourly energy balances, as BISE model already offers the opportunity to acquire hourly results for the solar output.

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# XI ANNEX A. REGIONAL DIVISION

This Annex presents regional division used in this dissertation. The list below provides details on 11 large regions and countries, which are included into each of them. Similar regional division is used, for example, in Urge-Vorsatz, Eyre, et al. (2012).

1. NAM = North America (Canada, Guam, Puerto Rico, United States of America, Virgin Islands)
2. WEU = Western Europe (Andorra, Austria, Azores, Belgium, Canary Islands, Channel Islands, Cyprus, Denmark, Faeroe Islands, Finland, France, Germany, Gibraltar, Greece, Greenland, Iceland, Ireland, Isle of Man, Italy, Liechtenstein, Luxembourg, Madeira, Malta, Monaco, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, United Kingdom)
3. PAO = Pacific OECD (Australia, Japan, New Zealand)
4. EEU = Central and Eastern Europe (Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, The former Yugoslav Rep. of Macedonia, Hungary, Poland, Romania, Slovak Republic, Slovenia, Yugoslavia)
5. FSU = Newly independent states of the former Soviet Union (Armenia, Azerbaijan, Belarus, Estonia, Georgia, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Republic of Moldova, Russian Federation, Tajikistan, Turkmenistan, Ukraine, Uzbekistan)
6. CPA = Centrally planned Asia and China (Cambodia, China (incl. Hong Kong), Korea (DPR), Laos (PDR), Mongolia, Viet Nam)
7. SAS = South Asia (Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, Sri Lanka)

8. PAS = Other Pacific Asia (American Samoa, Brunei Darussalam, Fiji, French Polynesia, Gilbert-Kiribati, Indonesia, Malaysia, Myanmar, New Caledonia, Papua, New Guinea, Philippines, Republic of Korea, Singapore, Solomon Islands, Taiwan (China), Thailand, Tonga, Vanuatu, Western Samoa)
9. MEA = Middle East and North Africa (Algeria, Bahrain, Egypt (Arab Republic), Iraq, Iran (Islamic Republic), Israel, Jordan, Kuwait, Lebanon, Libya/SPLAJ, Morocco, Oman, Qatar, Saudi Arabia, Sudan, Syria (Arab Republic), Tunisia, United Arab Emirates, Yemen)
10. LAC = Latin America and the Caribbean (Antigua and Barbuda, Argentina, Bahamas, Barbados, Belize, Bermuda, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, French Guyana, Grenada, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Saint Kitts and Nevis, Santa Lucia, Saint Vincent and the Grenadines, Suriname, Trinidad and Tobago, Uruguay, Venezuela)
11. AFR = Sub-Saharan Africa (Angola, Benin, Botswana, British Indian Ocean Territory, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Cote d'Ivoire, Congo, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Reunion, Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, Saint Helena, Swaziland, Tanzania, Togo, Uganda, Zaire, Zambia, Zimbabwe)

# XII ANNEX B. ADDITIONAL DATA ON ROOF AREA

Table 34 Roof-to-floor ratios by region and building type

| Region | Residential | | Commercial | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Single-family | Multifamily | Educational | Hotels & Restaurants | Hospitals | Retail | Offices | Others |
| **AFR** | 0.90 | 0.36 | 0.54 | 0.73 | 0.51 | 0.92 | 0.25 | 0.62 |
| **CPA** | 0.63 | 0.11 | 0.17 | 0.23 | 0.16 | 0.33 | 0.08 | 0.19 |
| **EEU** | 0.49 | 0.15 | 0.22 | 0.30 | 0.21 | 0.43 | 0.10 | 0.25 |
| **FSU** | 0.51 | 0.20 | 0.30 | 0.39 | 0.28 | 0.57 | 0.14 | 0.33 |
| **LAC** | 0.78 | 0.37 | 0.55 | 0.74 | 0.52 | 0.92 | 0.26 | 0.63 |
| **MEA** | 0.56 | 0.18 | 0.28 | 0.37 | 0.26 | 0.53 | 0.13 | 0.31 |
| **NAM** | 0.62 | 0.13 | 0.20 | 0.27 | 0.19 | 0.39 | 0.09 | 0.23 |
| **PAO** | 0.63 | 0.30 | 0.45 | 0.60 | 0.42 | 0.87 | 0.21 | 0.51 |
| **PAS** | 0.70 | 0.44 | 0.66 | 0.89 | 0.62 | 0.92 | 0.31 | 0.75 |
| **SAS** | 0.85 | 0.32 | 0.48 | 0.64 | 0.44 | 0.92 | 0.22 | 0.54 |
| **WEU** | 0.40 | 0.21 | 0.32 | 0.42 | 0.30 | 0.62 | 0.15 | 0.36 |

Table 35 Roof availability factors for installation of building-integrated solar technologies used in BISE model

| Building type in BISE Model | Type of built-up area | $AvF_f$ | $AvF_S$ |
|---|---|---|---|
| **Urban single-family** | M-L | 0.9 | 0.47 |
| **Urban multifamily** | H-H | 0.8 | 0.48 |
| **Urban C&P, educational** | M-M | 0.88 | 0.46 |
| **Urban C&P, hotels & restaurants** | H-M | 0.8 | 0.52 |
| **Urban C&P, hospitals** | M-M | 0.88 | 0.46 |
| **Urban C&P, other** | H-L | 0.85 | 0.51 |
| **Urban C&P, retail** | M-L | 0.9 | 0.47 |
| **Urban C&P, office** | VH-M | 0.95 | 0.38 |
| **Rural single-family** | L-L | 0.92 | 0.46 |
| **Rural C&P, educational** | M-L | 0.9 | 0.47 |
| **Rural C&P, hotels & restaurants** | M-L | 0.9 | 0.47 |
| **Rural C&P, hospitals** | M-L | 0.9 | 0.47 |
| **Rural C&P, other** | M-L | 0.9 | 0.47 |
| **Rural C&P, retail** | L-L | 0.92 | 0.46 |
| **Rural C&P, office** | H-L | 0.85 | 0.51 |

Source: Izquierdo et al. (2008)

Table 36. Residential roof area per capita available for solar system installations presented in different sources and for different regions in comparison to the results of BISE model

| Region | Source | Roof area per capita |
|---|---|---|
| **Austria** | AT (Lehmann & Peter 2003) | 12.1 |
| | AT (IEA 2002) | 10.4 |
| | AT (Defaix et al. 2012) | 5.7 |
| | AT (BISE model) | 6.2 |
| **Belgium** | BE (Lehmann & Peter 2003) | 11.8 |
| | BE (BISE model) | 7.1 |
| **Denmark** | DK (Lehmann & Peter 2003) | 12.7 |
| | DK (IEA 2002) | 9.3 |
| | DK (Defaix et al. 2012) | 7.8 |
| | DK (BISE model) | 5.8 |
| **Germany** | DE (Lehmann & Peter 2003) | 15.7 |
| | DE (IEA 2002) | 8.8 |
| | DE (Defaix et al. 2012) | 6.1 |
| | DE (BISE model) | 4.7 |
| **Finland** | FI (IEA 2002) | 14.9 |
| | DE (Lehmann & Peter 2003) | 14.4 |
| | FI (Defaix et al. 2012) | 4.8 |
| | FI (BISE model) | 6.4 |
| **France** | FR (Lehmann & Peter 2003) | 13.2 |
| | FR (BISE model) | 5.4 |
| **Spain** | ES (Ordóñez et al. 2010) | 25.9 |
| | ES (Izquierdo et.al. 2008) | 14.0 |
| | ES (Lehmann & Peter 2003) | 13.5 |
| | ES (IEA 2002) | 6.2 |
| | ES (Defaix et al. 2012) | 4.0 |
| | ES (BISE model) | 4.0 |
| **Greece** | GR (Lehmann & Peter 2003) | 12.8 |
| | GR (BISE model) | 3.7 |
| **Ireland** | IR (Lehmann & Peter 2003) | 14 |
| | IR (BISE model) | 6.6 |
| **Italy** | IT (Lehmann & Peter 2003) | 13 |
| | IT (IEA 2002) | 7.1 |
| | IT (Bergamasco and Asinari 2011) | 4.3 |
| | IT (Defaix et al. 2012) | 3.9 |
| | IT (BISE model) | 5.8 |
| **Luxemburg** | LU (Lehmann & Peter 2003) | 12.6 |
| | LU (BISE model) | 4.8 |
| **Netherlands** | NL (Lehmann & Peter 2003) | 11.6 |
| | NL (IEA 2002) | 7.7 |
| | NL (Defaix et al. 2012) | 6.7 |
| | NL (BISE model) | 6.7 |
| **Portugal** | PT (Lehmann & Peter 2003) | 13.9 |
| | PT (BISE model) | 4.8 |
| **Sweden** | SE (IEA 2002) | 14.9 |
| | SE (Lehmann & Peter 2003) | 14.7 |
| | SE (Defaix et al. 2012) | 6.4 |
| | SE (BISE model) | 6.0 |
| **Slovakia** | SK (Hofierka and Kaňuk 2009) | 6.0 |
| | SK (BISE model) | 4.5 |
| **UK** | UK (IEA 2002) | 9.9 |
| | UK (Highman 2011) | 9.9 |

| Region | Source | Roof area per capita |
|---|---|---|
| | UK (Defaix et al. 2012) | 6.6 |
| | UK (BISE model) | 5.5 |
| **WEU & EEU** | Europe OECD (Hoogwijk 2004) | 27.0 |
| | Europe C&W (Eiffert 2003) | 18.0 |
| | Europe C&W  (IEA 2002) | 9.0 |
| | WEU&EEU (BISE model) | 5.1 |
| **WEU** | CH (Montavon et.al. 2004) | 12.1 |
| | CH (Montavon et.al. 2004) | 18.8 |
| | CH (Montavon et.al. 2004) | 10.8 |
| | CH (IEA 2002) | 8.9 |
| | WEU (BISE model) | 5.2 |
| **US** | US (Eiffert 2003) | 36.0 |
| | US  (Hoogwijk 2004) | 29.0 |
| | US (IEA 2002) | 22.4 |
| | US (BISE model) | 14.0 |
| **NAM** | CA (Hoogwijk 2004) | 23.0 |
| | CA (Wiginton, Nguyen, and Pearce 2010) | 13.1 |
| | CA (IEA 2002) | 1.1 |
| | NAM  (BISE model) | 13.8 |
| **PAS** | Oceania (Hoogwijk 2004) | 20.0 |
| | TW (Yue and Huang 2011) | 8.2 |
| | PAS (BISE model) | 2.0 |
| **PAO** | AU (Eiffert 2003) | 36.0 |
| | AU (IEA 2002) | 18.1 |
| | JP (Eiffert 2003) | 8.0 |
| | JP (IEA 2002) | 5.9 |
| | PAO (BISE model) | 7.3 |
| **LAC** | South America  (Hoogwijk 2004) | 10.0 |
| | LAC (BISE model) | 2.4 |

*Note*: AT – Austria, BE – Belgium, DK – Denmark, DE – Germany, FI – Finland, FR – France, ES – Spain, GR – Greece, IR – Ireland, IT – Italy, LU – Luxemburg, NL – Netherlands, PT – Portugal, SE – Sweden, SK – Slovakia, UK – United Kingdom, US – United States, CH – Switzerland, CA – Canada, TW – Taiwan, AU – Australia, JP – Japan

# XIII ANNEX C. LIST OF APPLIANCES FROM BUENAS MODEL

Table 37 presents the types of appliances for commercial and residential sectors, for which the data on energy use was available in BUENAS model for presented countries.

Table 37. Types of appliances, for which data are available in the BUENAS model by country

| COUNTRY | APPLIANCES | |
|---|---|---|
| | *Commercial* | *Residential* |
| **Brazil** | Refrigeration | Fan\Fan |
| | | Refrigerator\Refrigerator |
| | | Standby\Standby |
| | | Television\CRT\CRT |
| | | Television\LCD\LCD |
| | | Television\Plasma\Plasma |
| **Australia** | Refrigeration | Fan\Fan |
| | | Refrigerator\Refrigerator |
| | | Standby\Standby |
| | | Television\CRT\CRT |
| | | Television\LCD\LCD |
| | | Television\Plasma\Plasma |
| **China** | Refrigeration | Cooking Products\Electric Stove |
| | | Fan\Fan |
| | | Refrigerator\Refrigerator |
| | | Standby\Standby |
| | | Television\CRT\CRT |
| | | Television\LCD\LCD |
| | | Television\Plasma\Plasma |
| | | Washing Machine\Washing Machine |
| **EU** | Refrigeration | Clothes Dryers\Electric Clothes Dryers {EU} |
| | | Cooking Products\Dishwasher {EU SA} |
| | | External Power Supplies\External Power Supplies |
| | | Fan\Fan |
| | | Freezers\Freezers |
| | | Refrigerator\Refrigerator |
| | | Set Top Boxes\Simple Set Top Boxes {EU} Digital TV adaptor {Canada} |
| | | Standby\Standby |
| | | Television\CRT\CRT |
| | | Television\LCD\LCD |
| | | Television\Plasma\Plasma |
| **India** | Refrigeration | Fan\Fan |
| | | Refrigerator\Refrigerator |
| | | Standby\Standby |
| | | Television\CRT\CRT |
| | | Television\LCD\LCD |
| **Indonesia** | Refrigeration | Fan\Fan |
| | | Refrigerator\Refrigerator |
| | | Standby\Standby |

| COUNTRY | | APPLIANCES |
|---|---|---|
| | | Television\CRT\CRT |
| | | Television\LCD\LCD |
| **Japan** | Refrigeration | Fan\Fan |
| | | Refrigerator\Refrigerator |
| | | Standby\Standby |
| | | Television\CRT\CRT |
| | | Television\LCD\LCD |
| **Mexico** | Refrigeration | Fan\Fan |
| | | Refrigerator\Refrigerator |
| | | Standby\Standby |
| | | Television\CRT\CRT |
| | | Television\LCD\LCD |
| | | Television\Plasma\Plasma |
| | | Washing Machine\Washing Machine |
| **Russia** | Refrigeration | Fan\Fan |
| | | Refrigerator\Refrigerator |
| | | Standby\Standby |
| | | Television\CRT\CRT |
| | | Television\LCD\LCD |
| | | Television\Plasma\Plasma |
| **South Africa** | Refrigeration | Clothes Dryers\Electric Clothes Dryers {SA} |
| | | Cooking Products\Dishwasher {EU SA} |
| | | Cooking Products\Electric Cooking Products {US} |
| | | Cooking Products\Electric Oven {SA} |
| | | Fan\Fan |
| | | Freezers\Freezers |
| | | Refrigerator\Refrigerator |
| | | Standby\Standby |
| | | Television\CRT\CRT |
| | | Television\LCD\LCD |
| | | Television\Plasma\Plasma |
| | | Washing Machine\Washing Machine |
| **US** | Refrigeration | Clothes Dryers\Electric Clothes Dryers {US} |
| | | Cooking Products\Electric Cooking Products {US} |
| | | Cooking Products\Electric Oven {SA} |
| | | Fan\Fan |
| | | Freezers\Freezers {US} |
| | | Furnace\Furnace {US}\Furnace EF {US} |
| | | Furnace\Furnace Fan {US}\Furnace Fan MHF {US} |
| | | Furnace\Furnace Fan {US}\Furnace Fan NWGF {US} |
| | | Furnace\Furnace Fan {US}\Furnace Fan OF {US} |
| | | Refrigerator\Refrigerator |
| | | Standby\Standby |
| | | Television\CRT\CRT {US} |
| | | Television\LCD\LCD {US} |
| | | Television\Plasma\Plasma {US} |
| | | Washing Machine\Washing Machine {US} |

*Note*: the appliance types highlighted in red were not considered in BISE model in order to maintain consistency in the set of selected appliances among the countries.

# XIV ANNEX D. SELECTED INTERMEDIATE RESULTS OF BISE MODEL

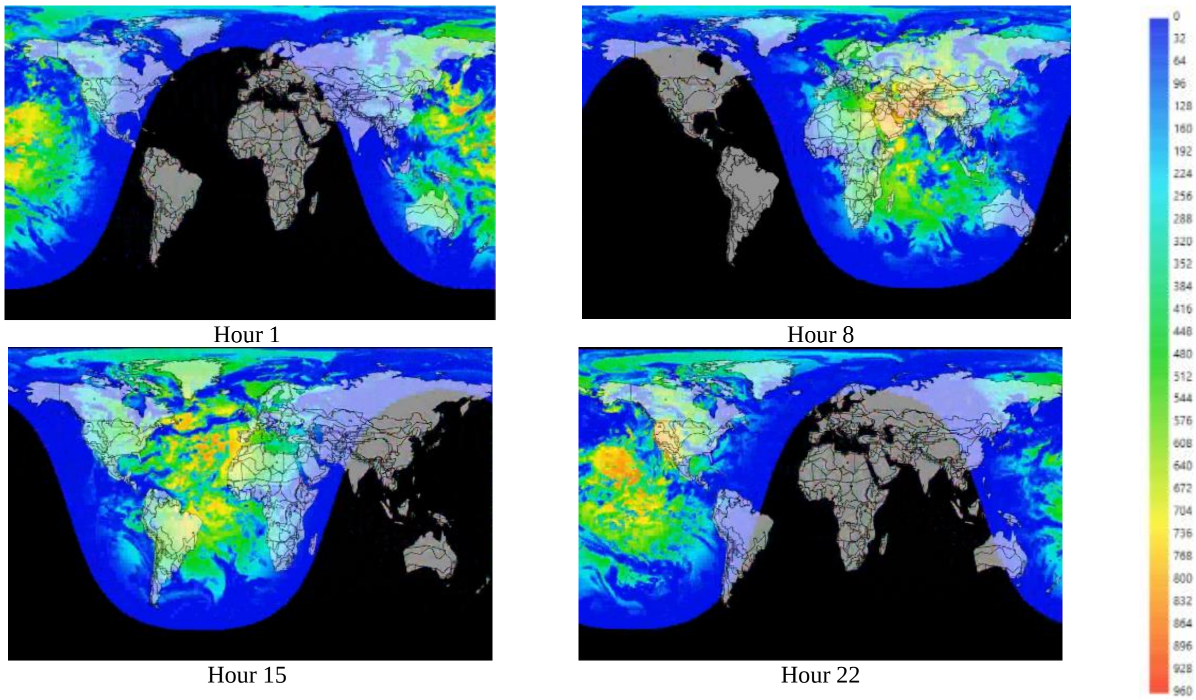


Figure 81. Hourly beam solar radiation, July 1st, 2005

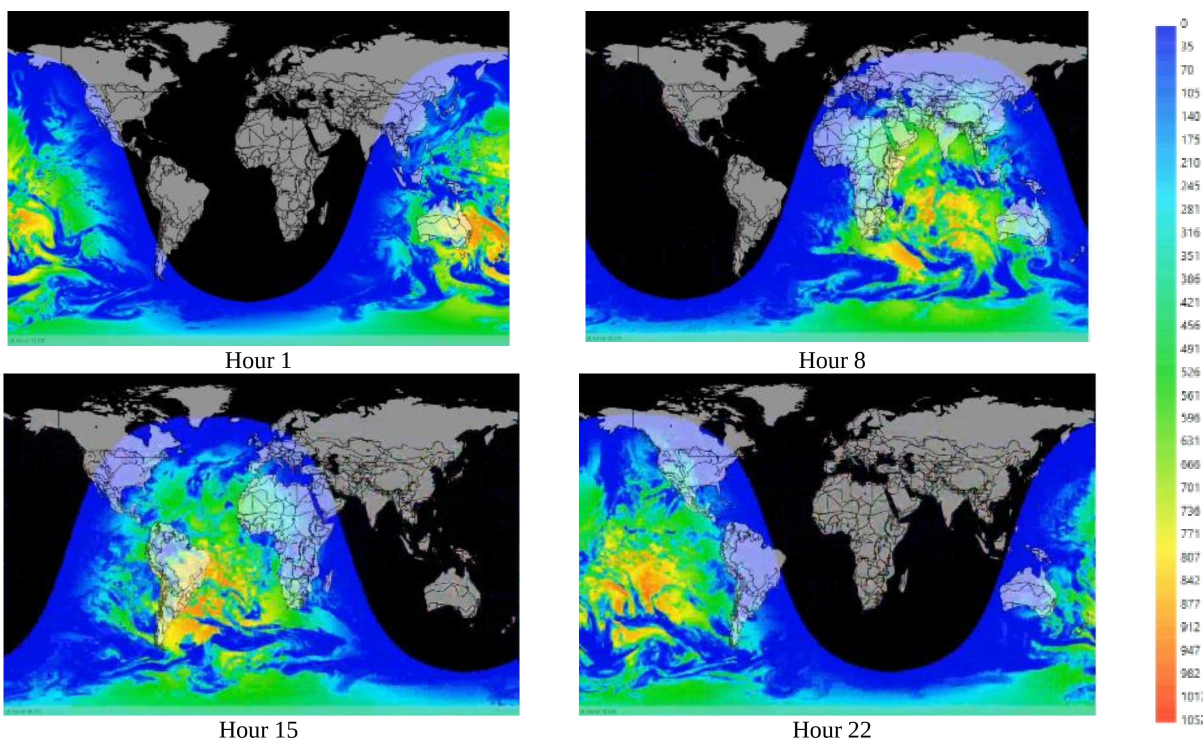


Figure 82. Hourly beam solar radiation, January 1st, 2005

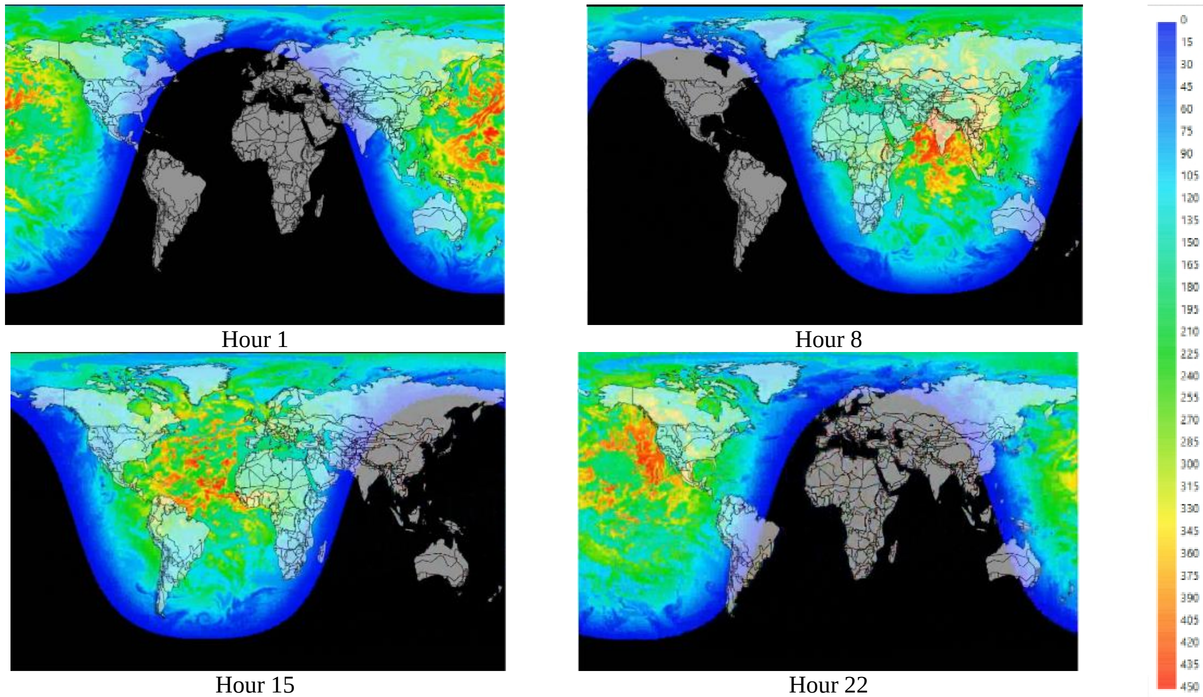


Figure 83. Hourly diffuse solar radiation, July 1st, 2005

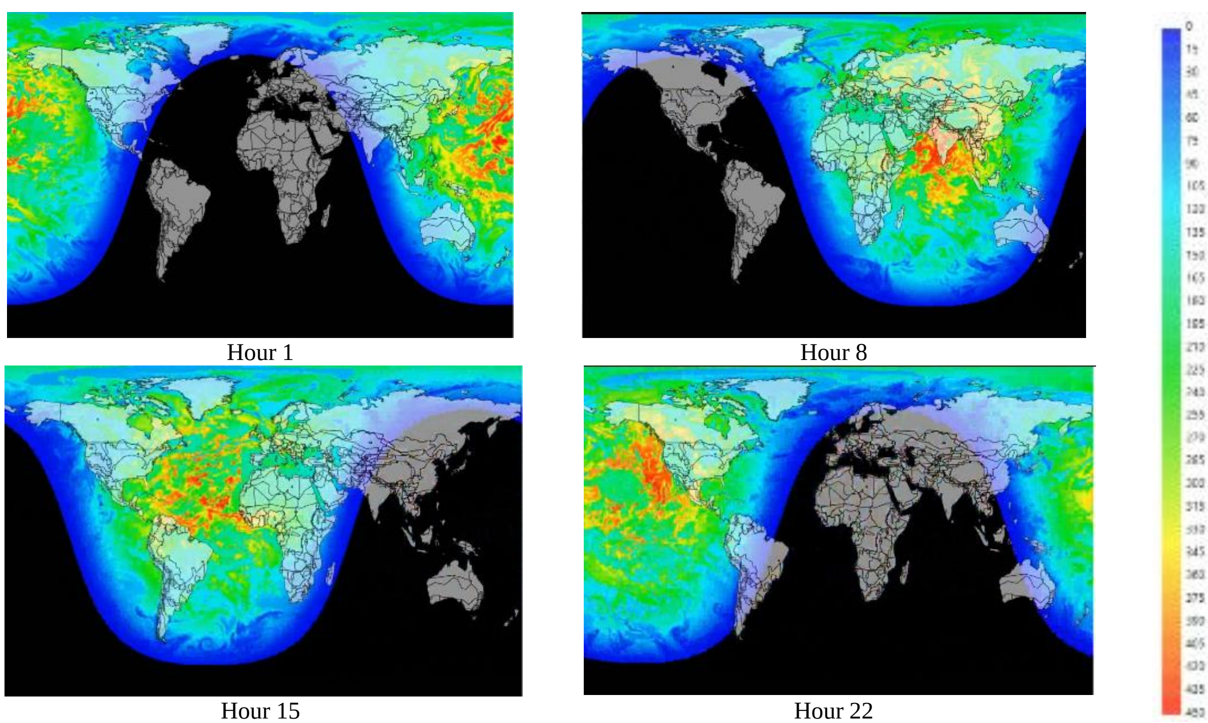


Figure 84. Hourly diffuse solar radiation, January 1st, 2005

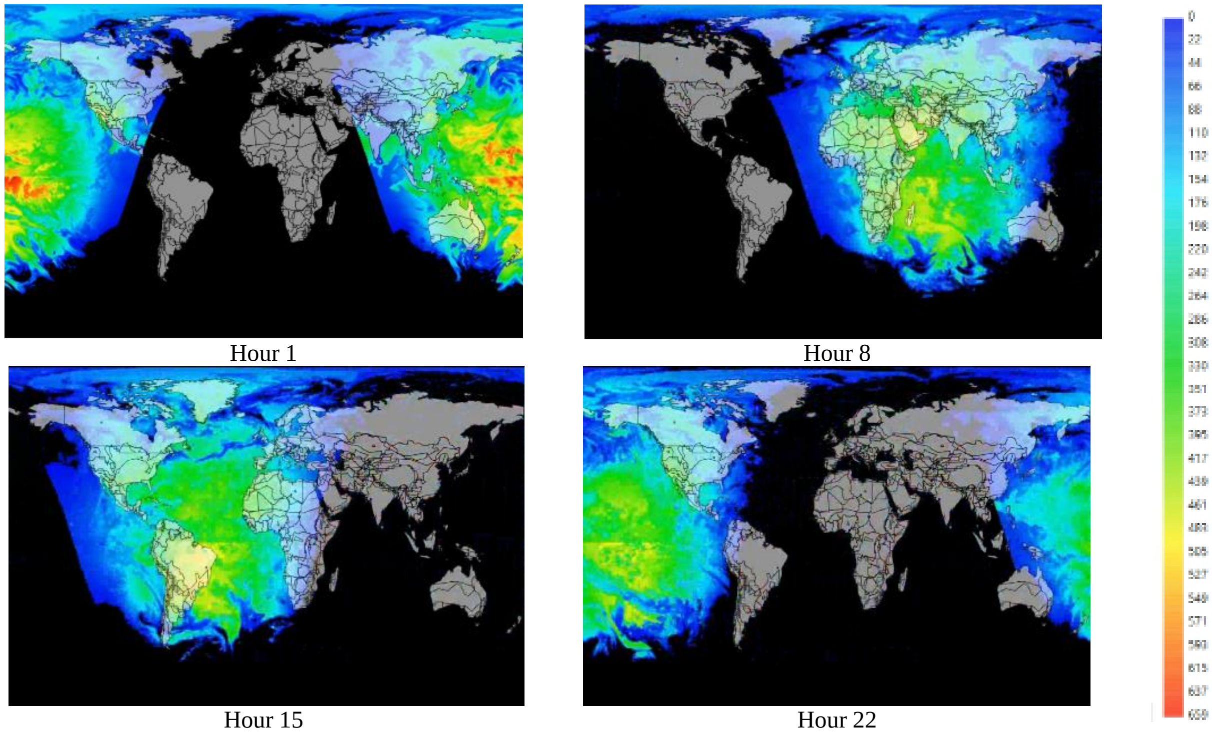

Figure 85. Hourly solar thermal energy output, July 1st, 2005

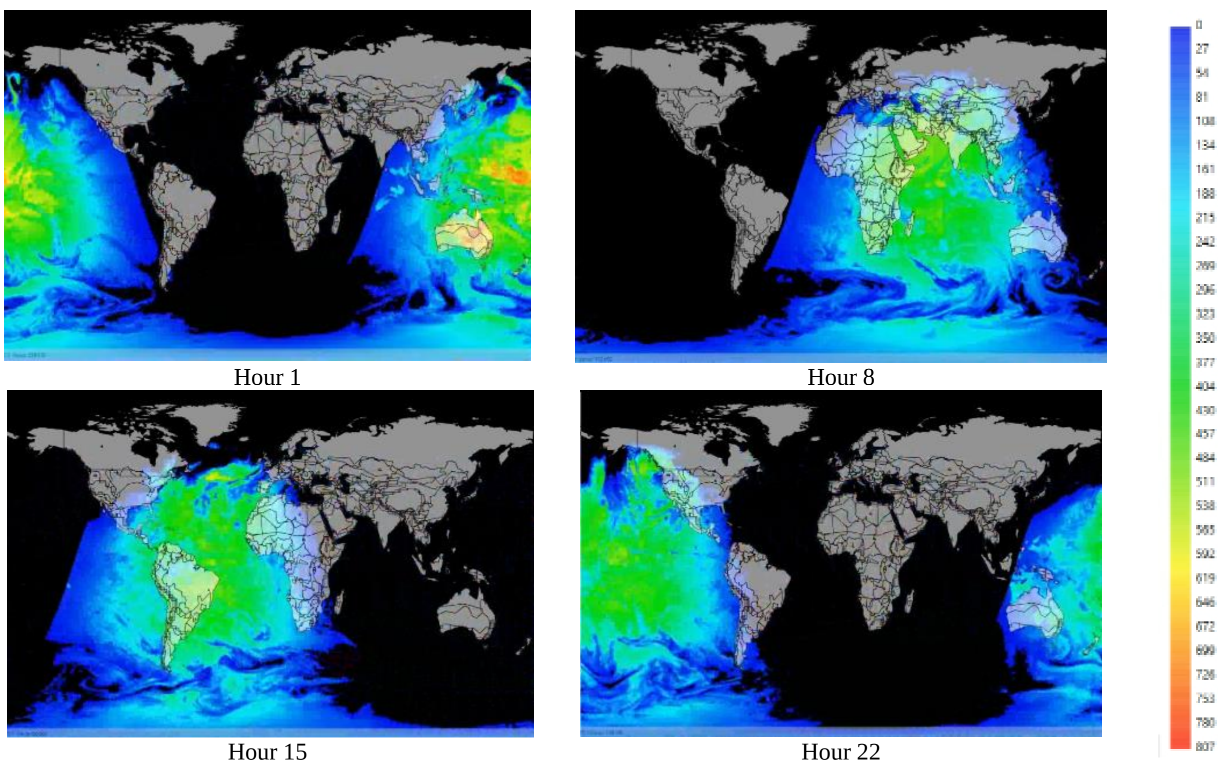

Figure 86. Hourly solar thermal energy output, January 1st, 2005

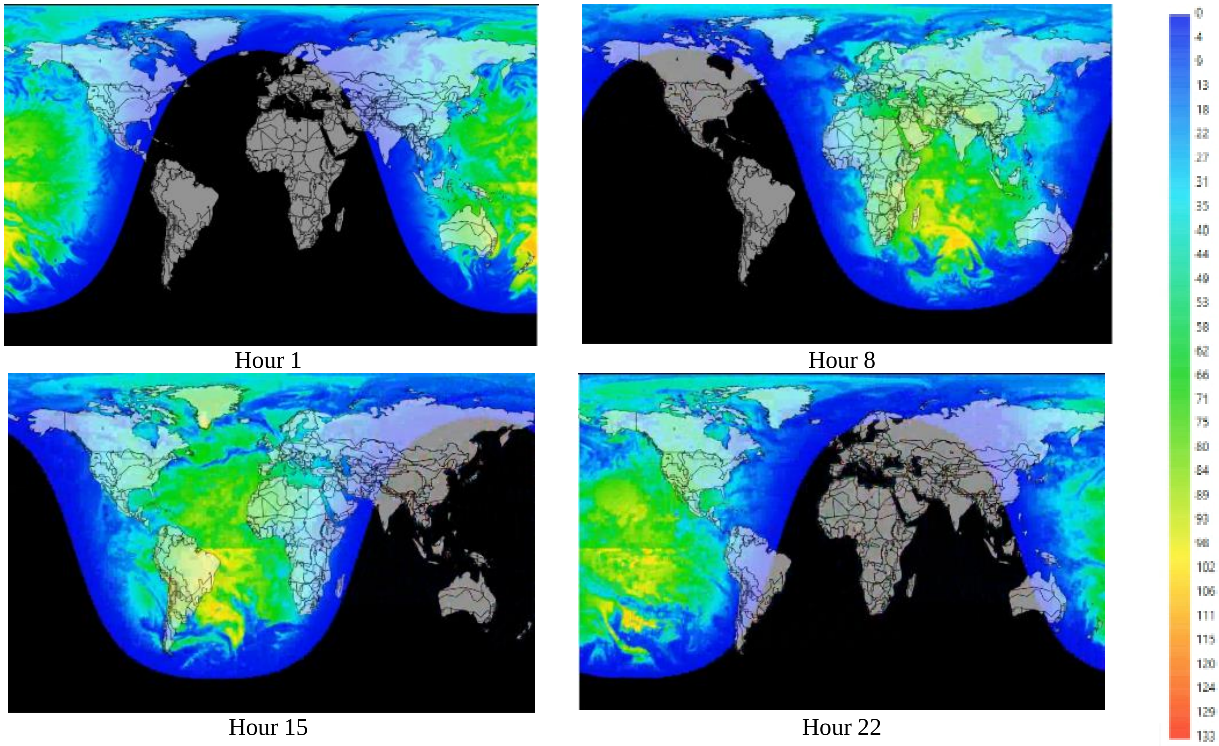


Figure 87. Hourly solar electric energy output, July 1st, 2005

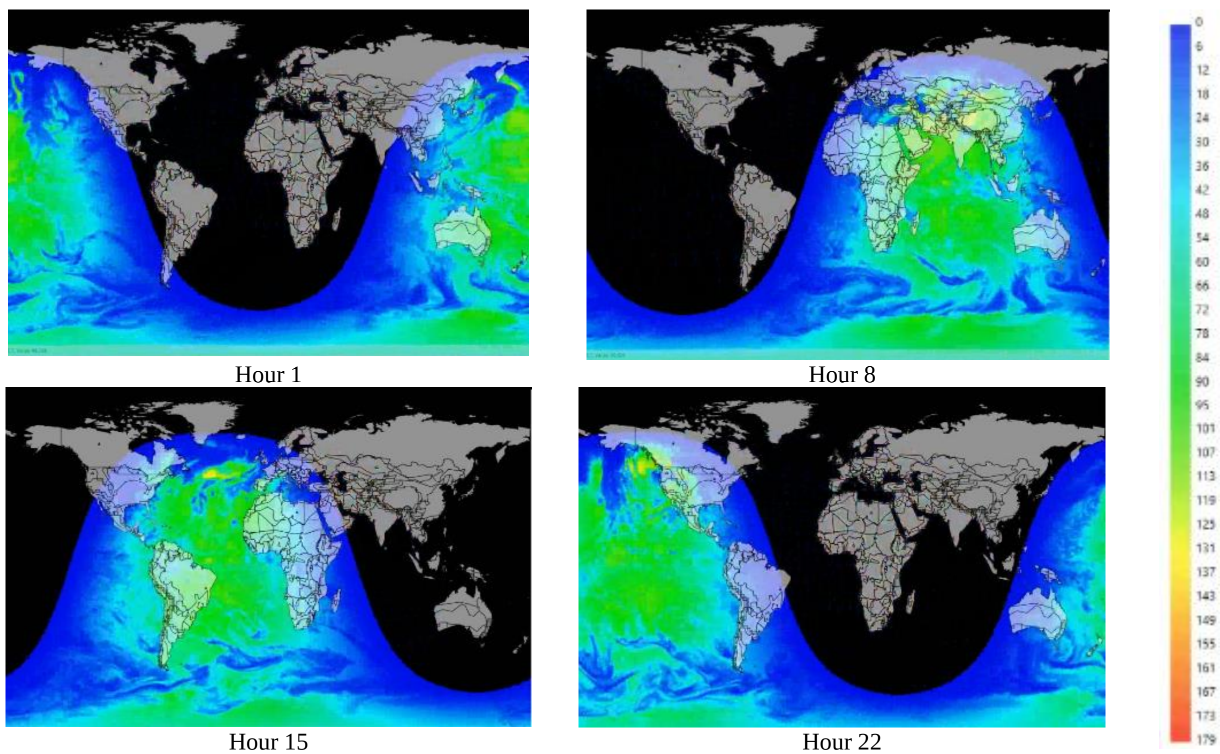


Figure 88. Hourly solar electric energy output, January 1st, 2005

# XV ANNEX E. ADDITIONAL RESULTS FROM BISE MODEL

## XV.1 Additional results for the regions

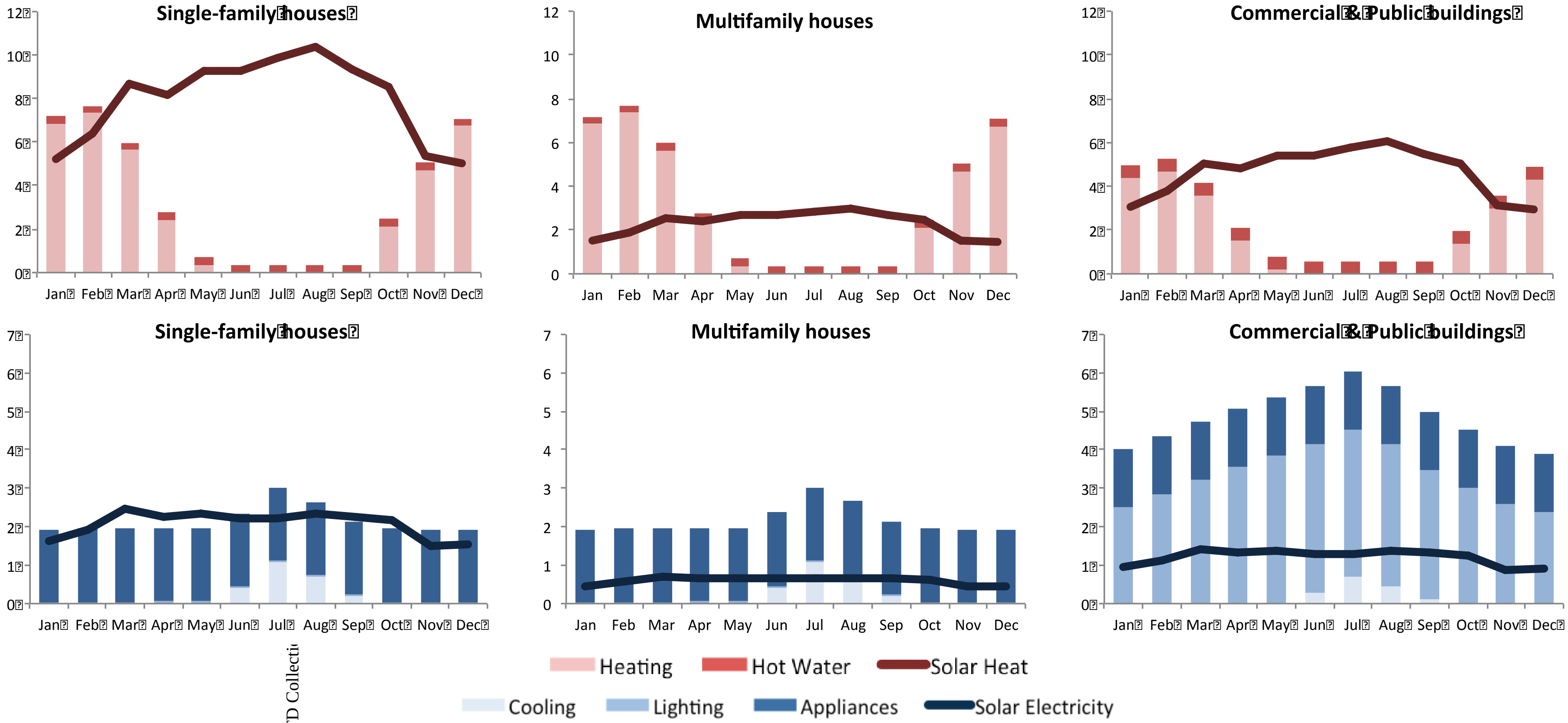


Figure 89. Energy use for different end-uses vs solar energy production in 2050 by building type, kWh per m2 of the floor area, Eastern Europe, Deep scenario

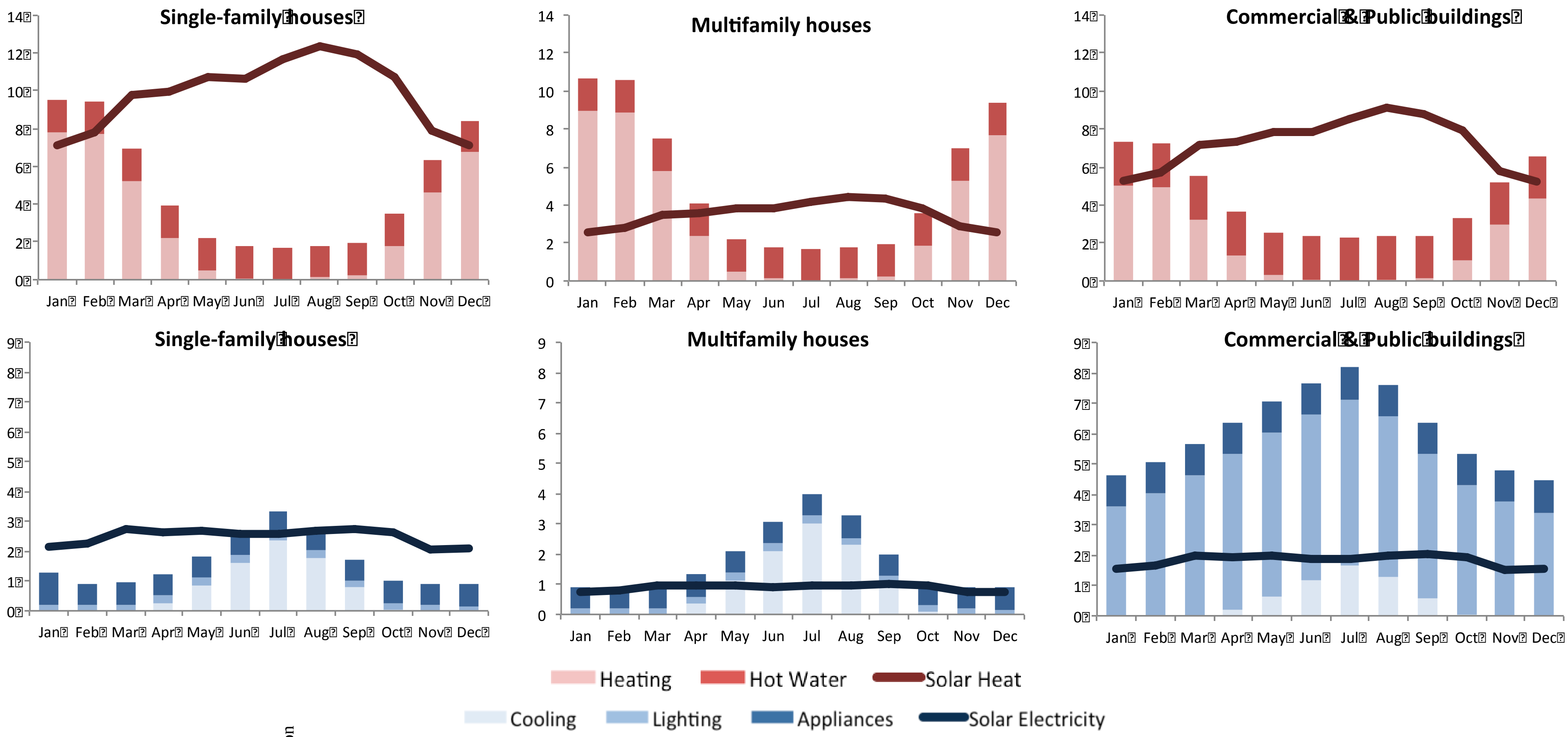


Figure 90. Energy use for different end-uses vs solar energy production in 2050 by building type, kWh per m2 of the floor area, Former Soviet Union, Deep scenario

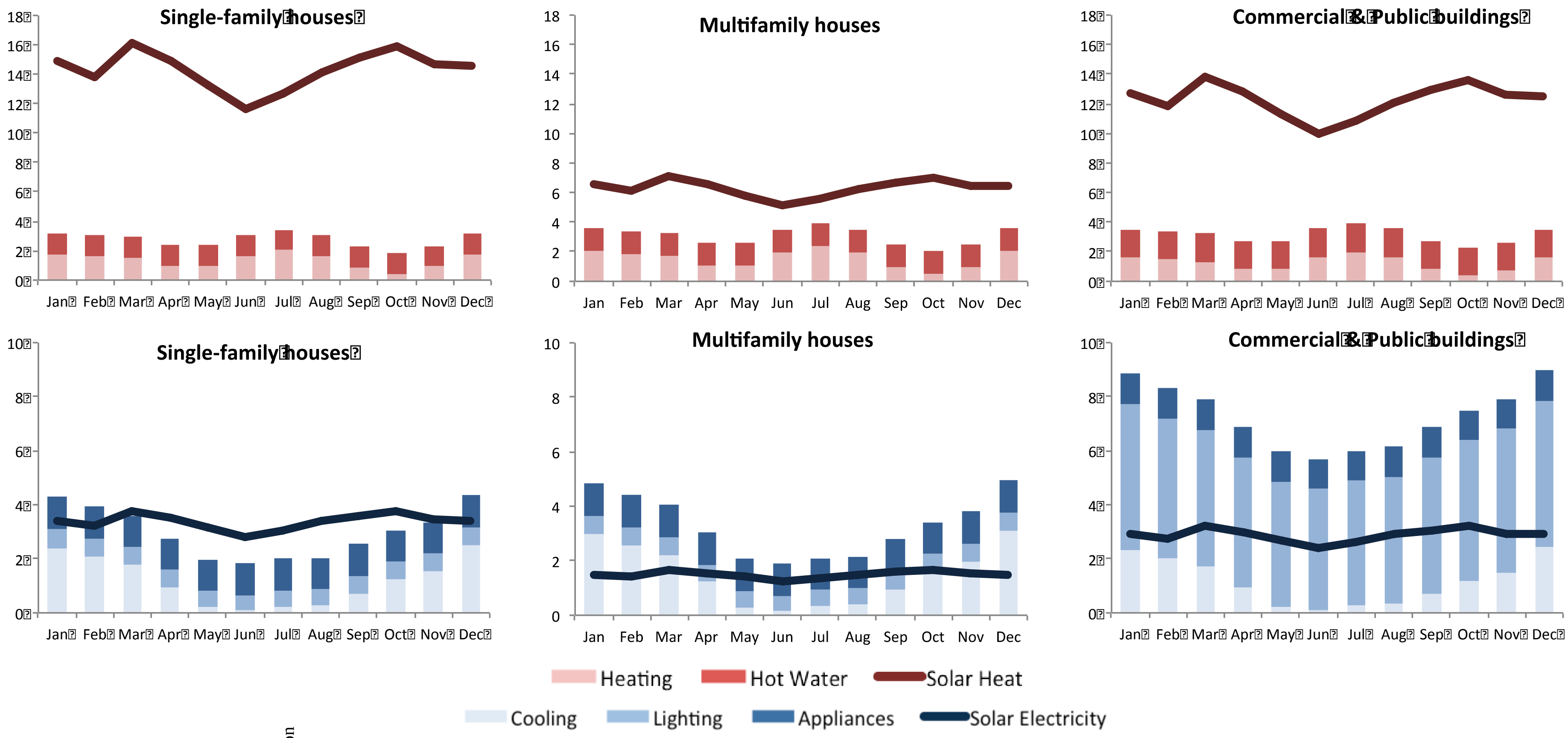


Figure 91. Energy use for different end-uses vs solar energy production in 2050 by building type, kWh per m2 of the floor area, Pacific OECD, Deep scenario

Figure 92. Energy use for different end-uses vs solar energy production in 2050 by building type, kWh per m2 of the floor area, Other Pacific Asia, Deep scenario

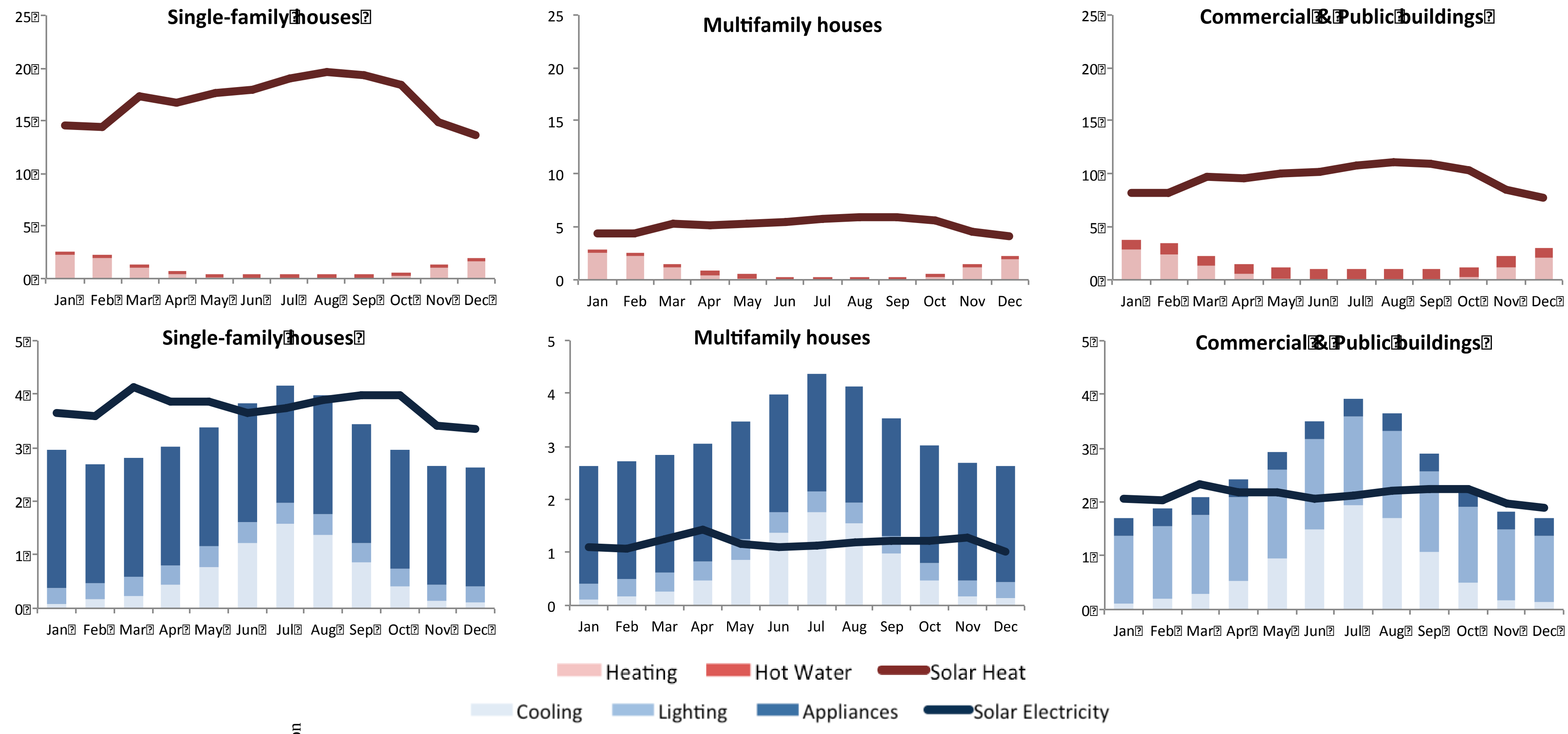


Figure 93. Energy use for different end-uses vs solar energy production in 2050 by building type, kWh per m2 of the floor area, Middle East, Deep scenario

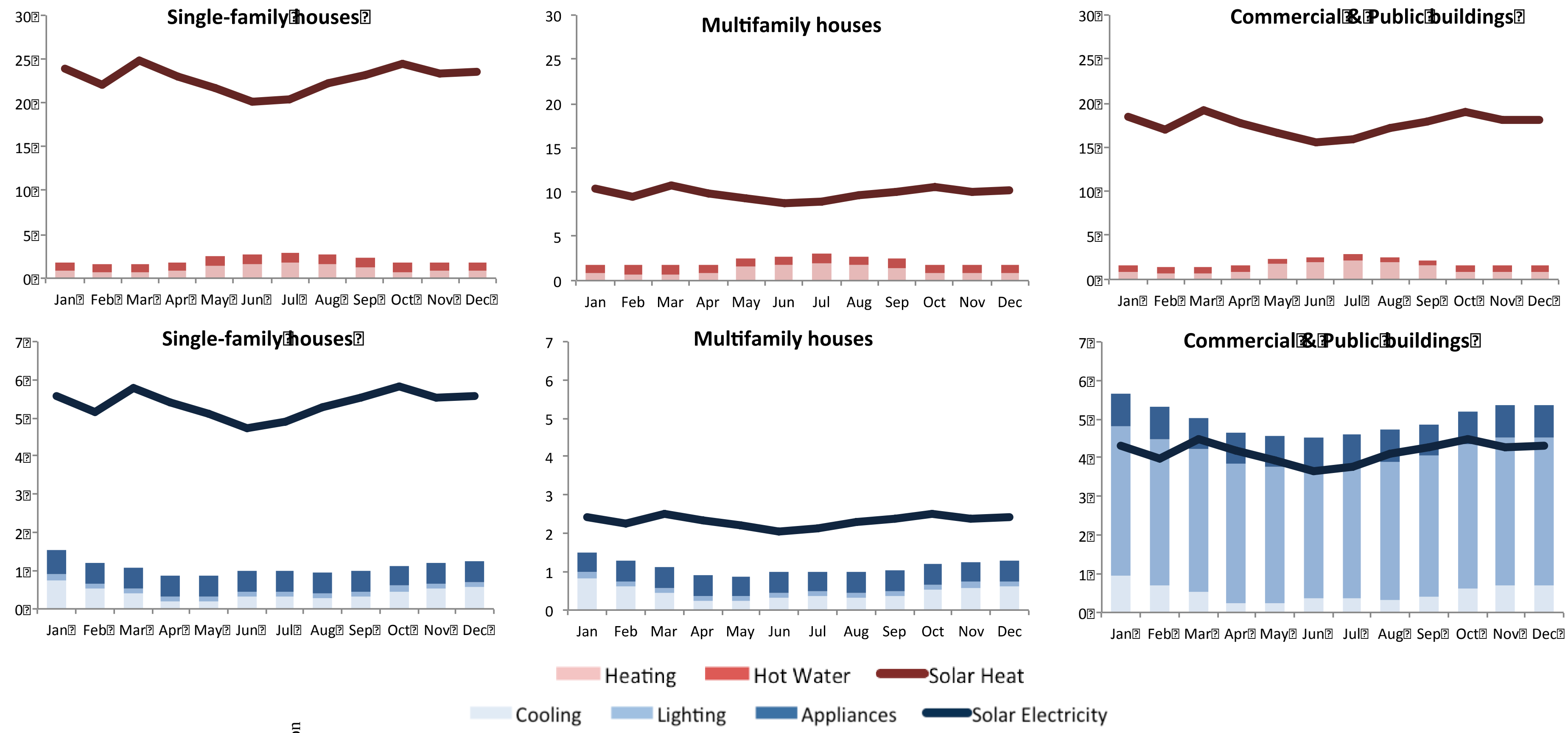


Figure 94. Energy use for different end-uses vs solar energy production in 2050 by building type, kWh per m2 of the floor area, Latin America and Caribbean, Deep scenario

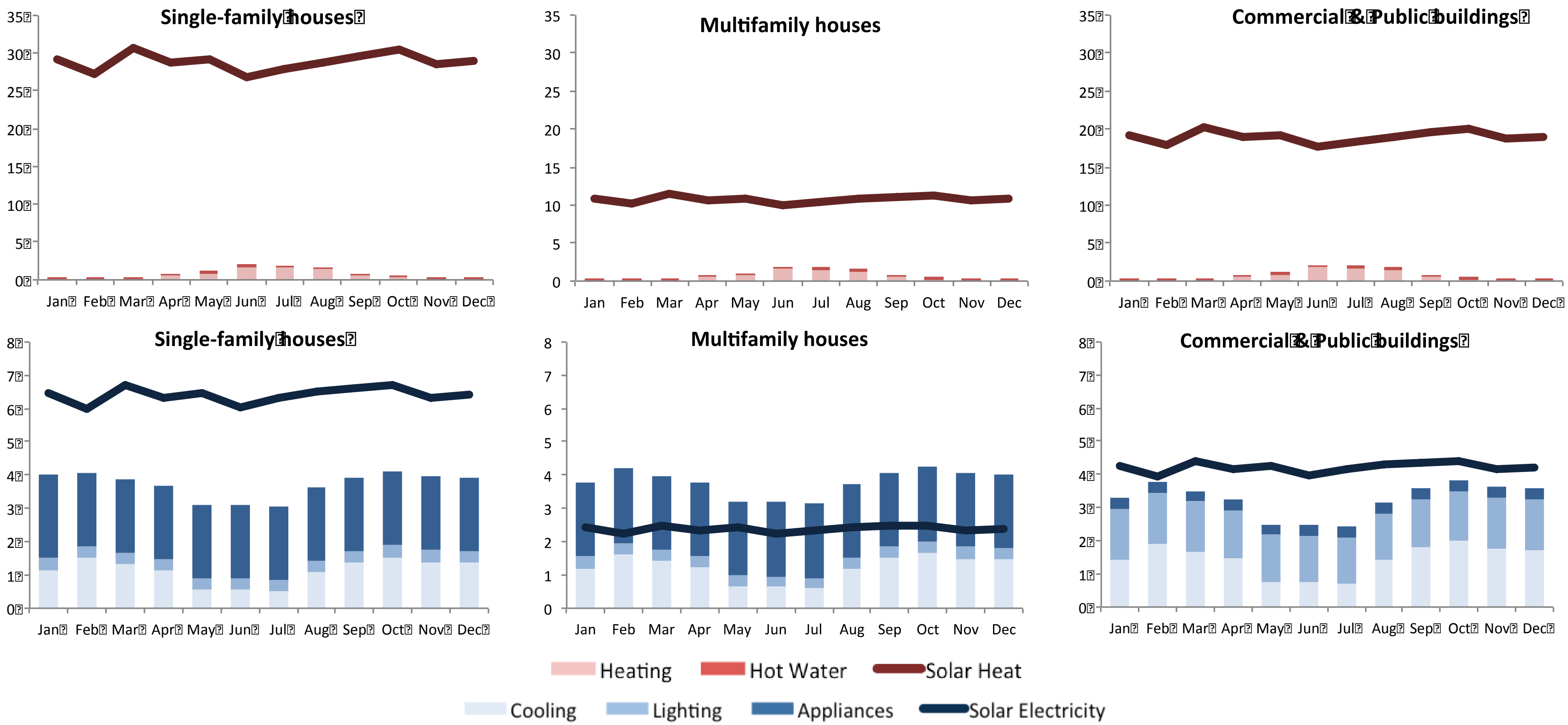


Figure 95. Energy use for different end-uses vs solar energy production in 2050 by building type, kWh per m2 of the floor area, Sub-Saran Africa, Deep scenario

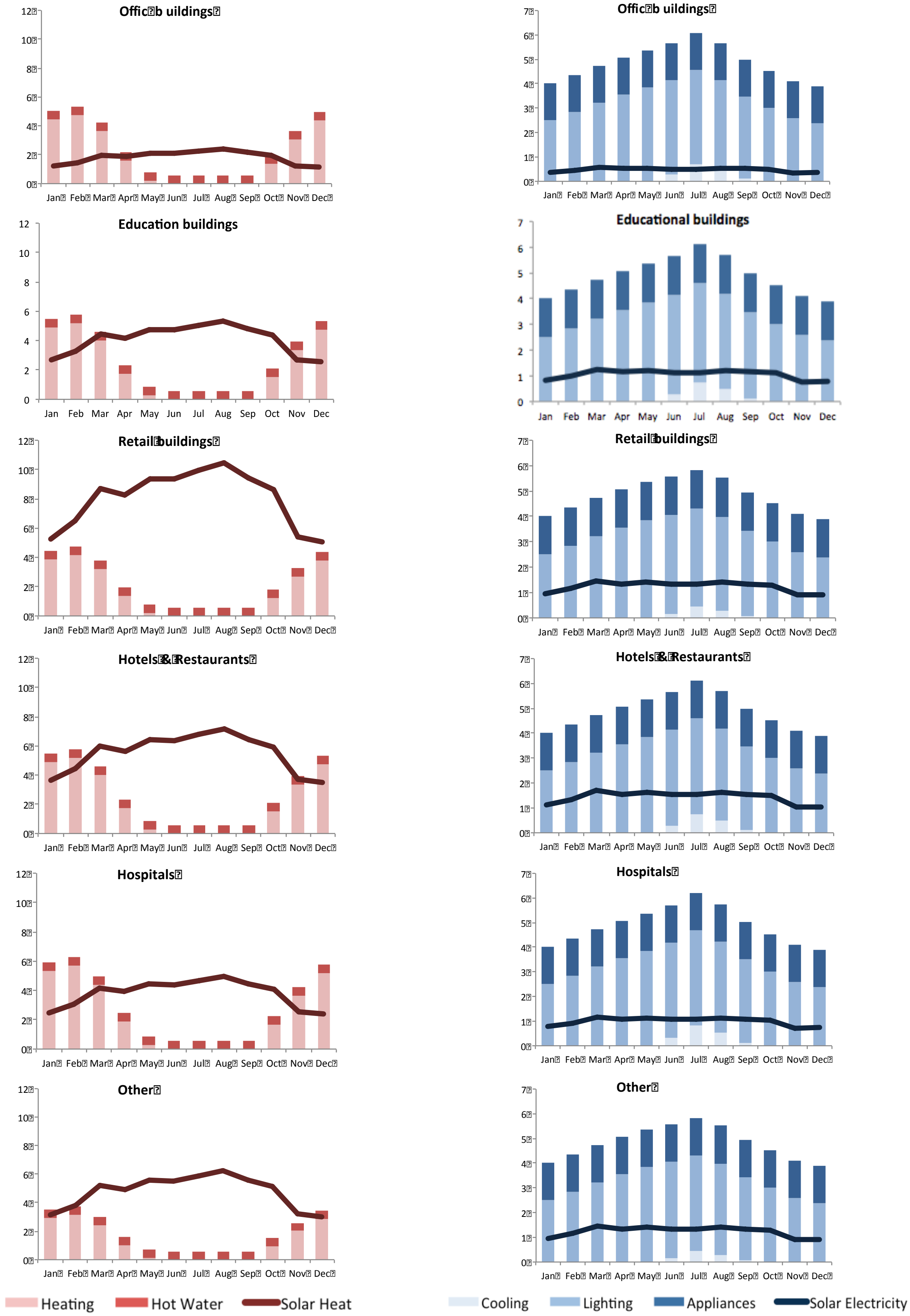


Figure 96. Energy use vs solar energy production in 2050 by C&P sub-category, kWh/m2 of floor area, EEU, Deep scenario

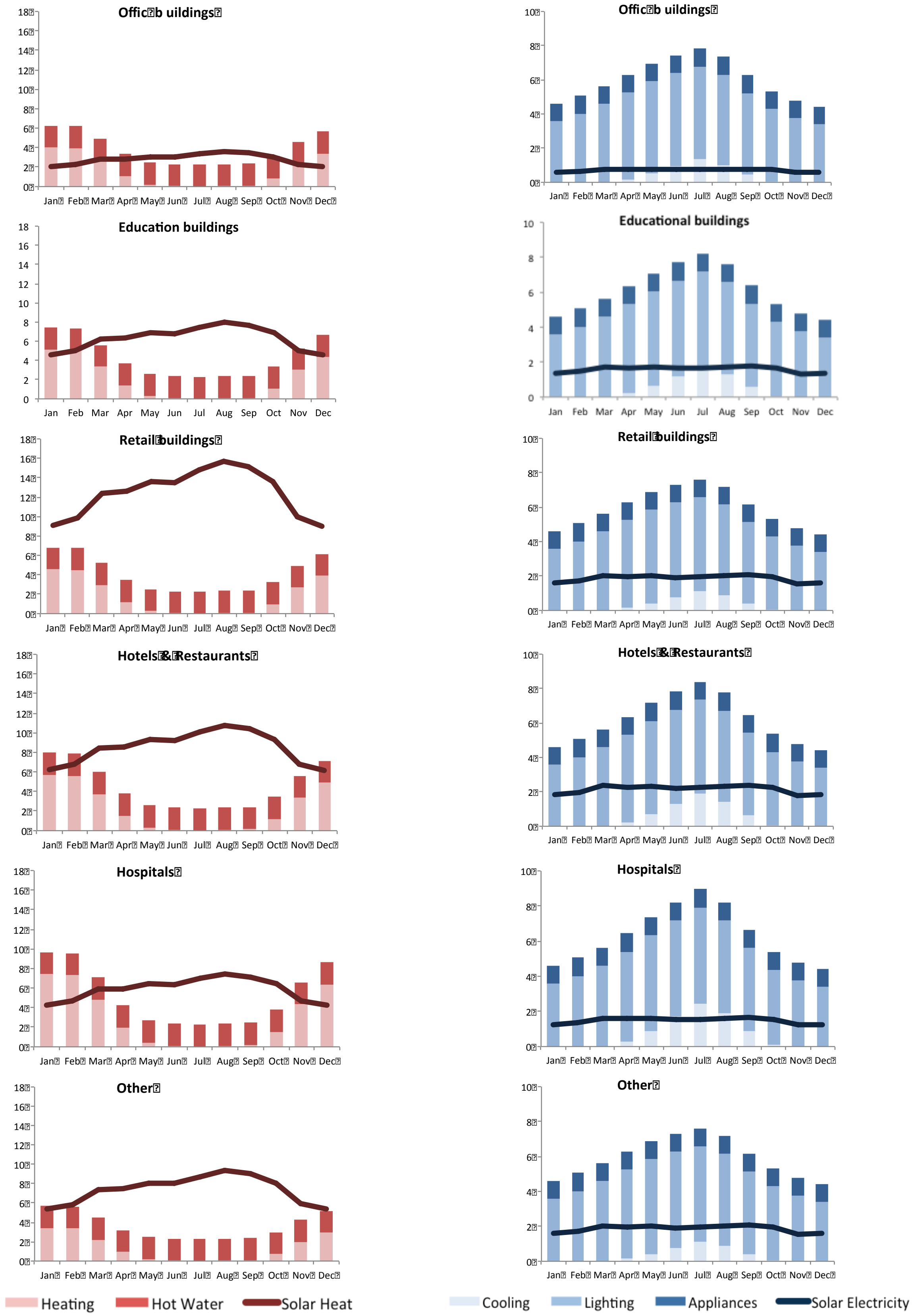


Figure 97. Energy use vs solar energy production in 2050 by C&P sub-category, kWh/m2 of floor area, FSU, Deep scenario

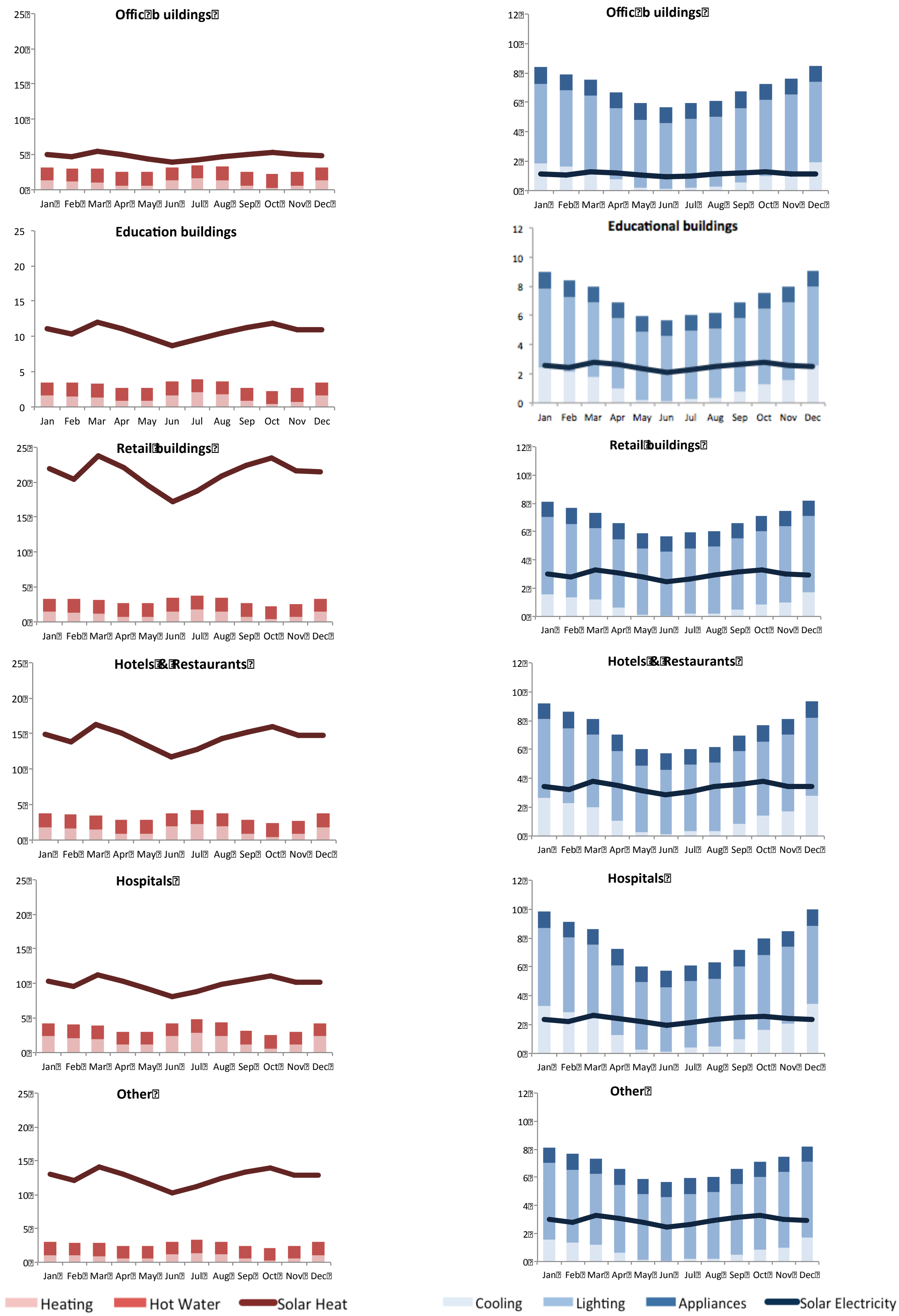


Figure 98. Energy use vs solar energy production in 2050 by C&P sub-category, kWh/m2 of floor area, PAO, Deep scenario

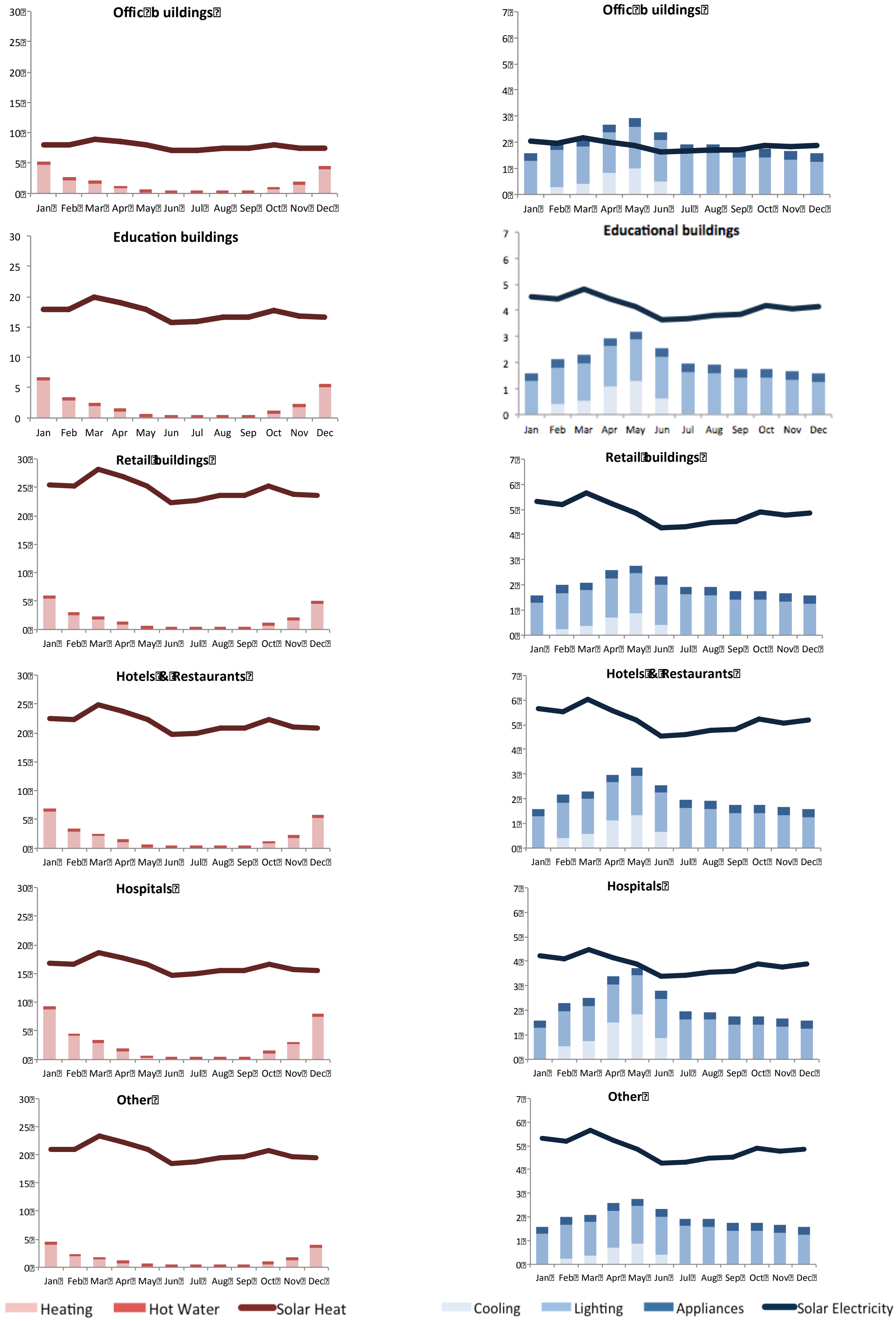


Figure 99. Energy use vs solar energy production in 2050 by C&P sub-category, kWh/m2 of floor area, PAS, Deep scenario

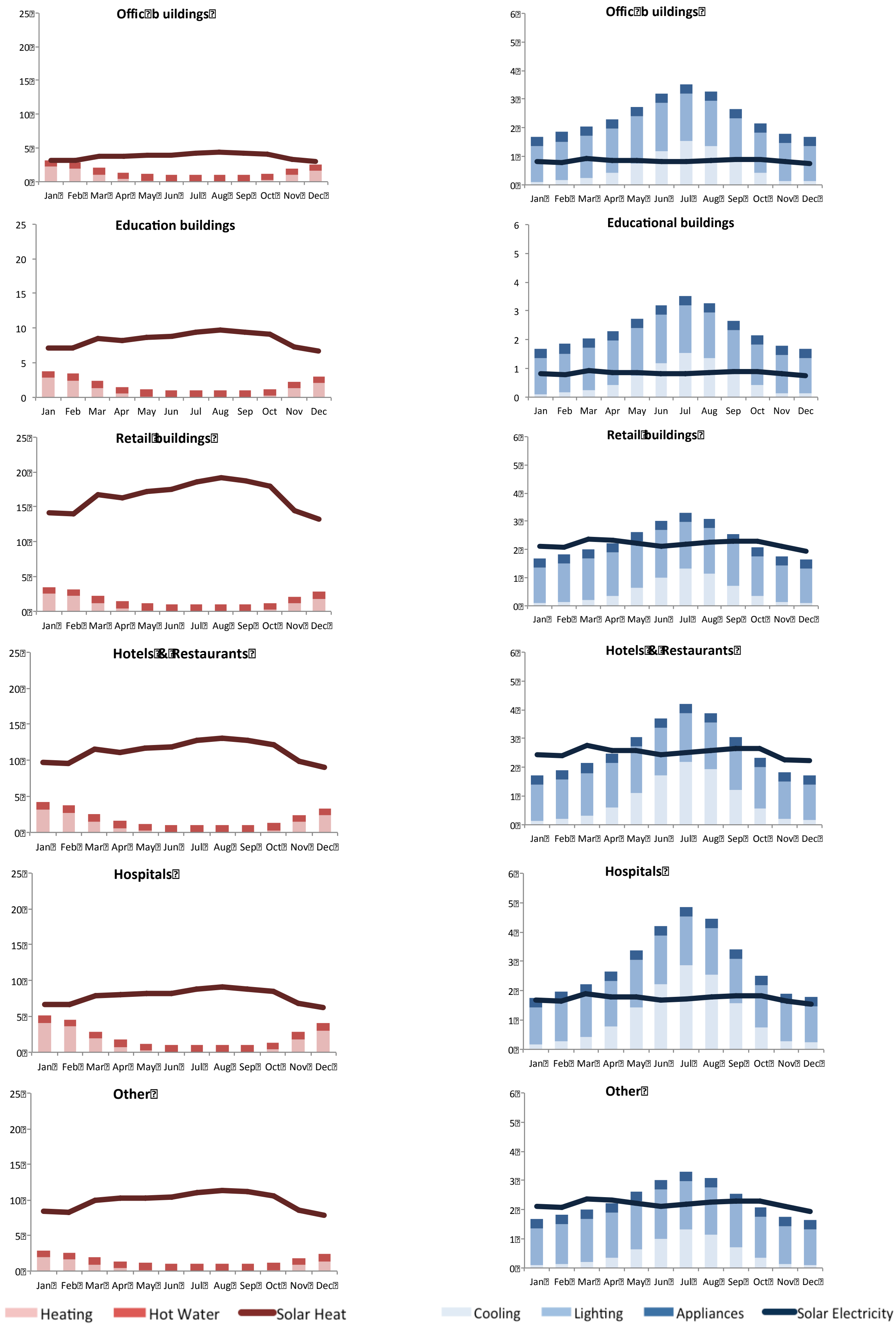


Figure 100. Energy use vs solar energy production in 2050 by C&P sub-category, kWh/m2 of floor area, MEA, Deep scenario

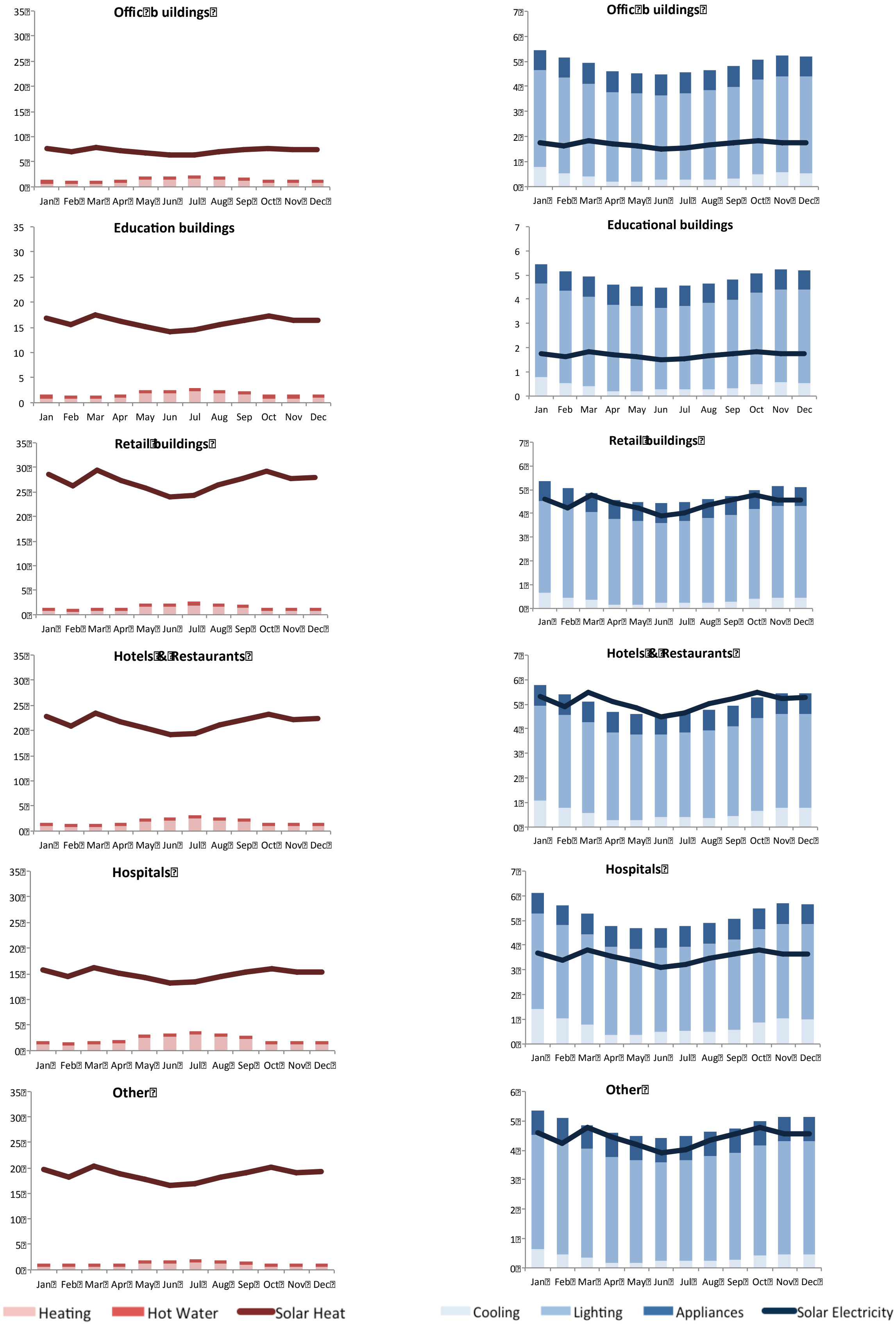


Figure 101. Energy use vs solar energy production in 2050 by C&P sub-category, kWh/m2 of floor area, LAC, Deep scenario

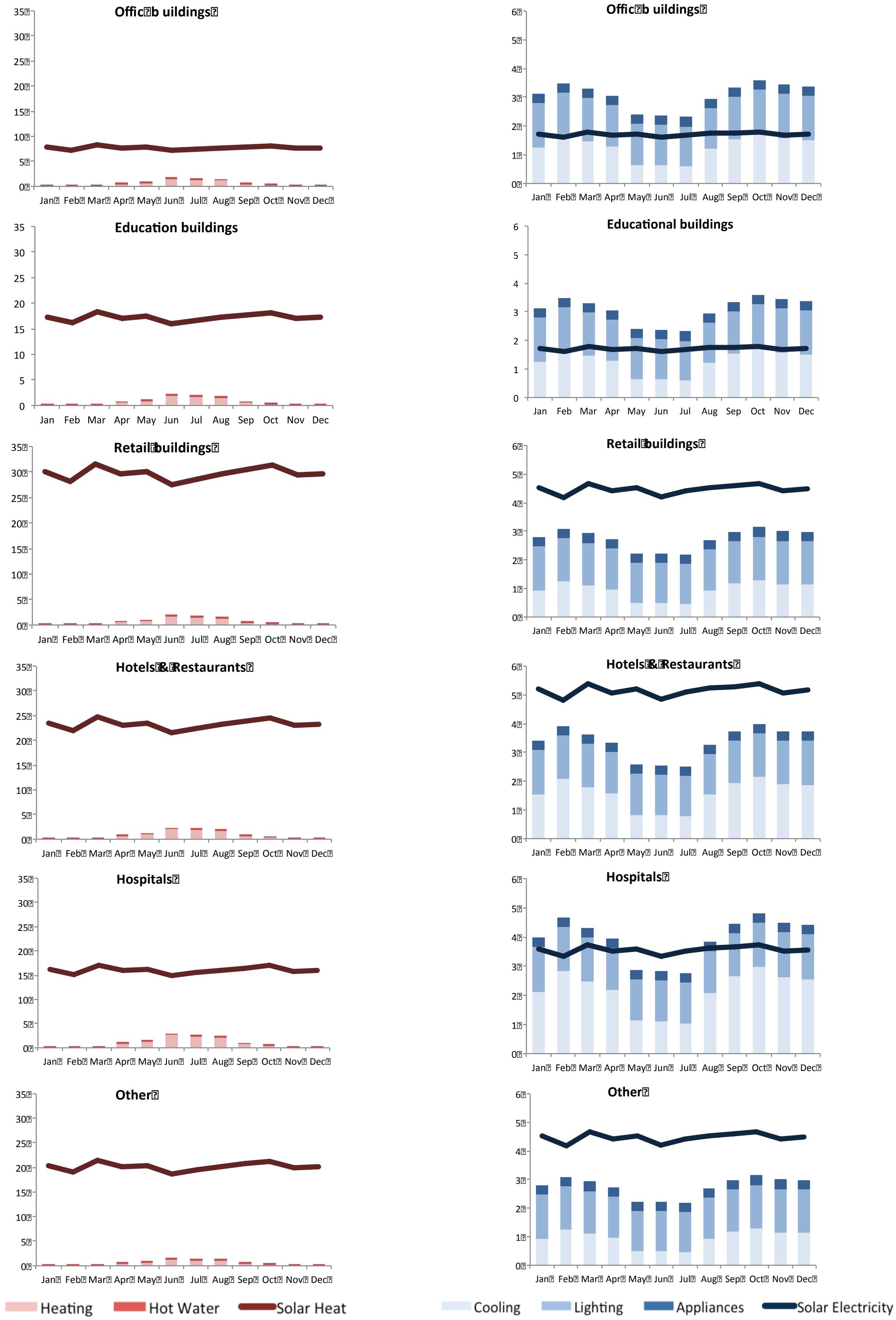


Figure 102. Energy use vs solar energy production in 2050 by C&P sub-category, kWh/m2 of floor area, AFR, Deep scenario

## XV.2 Additional results for the world

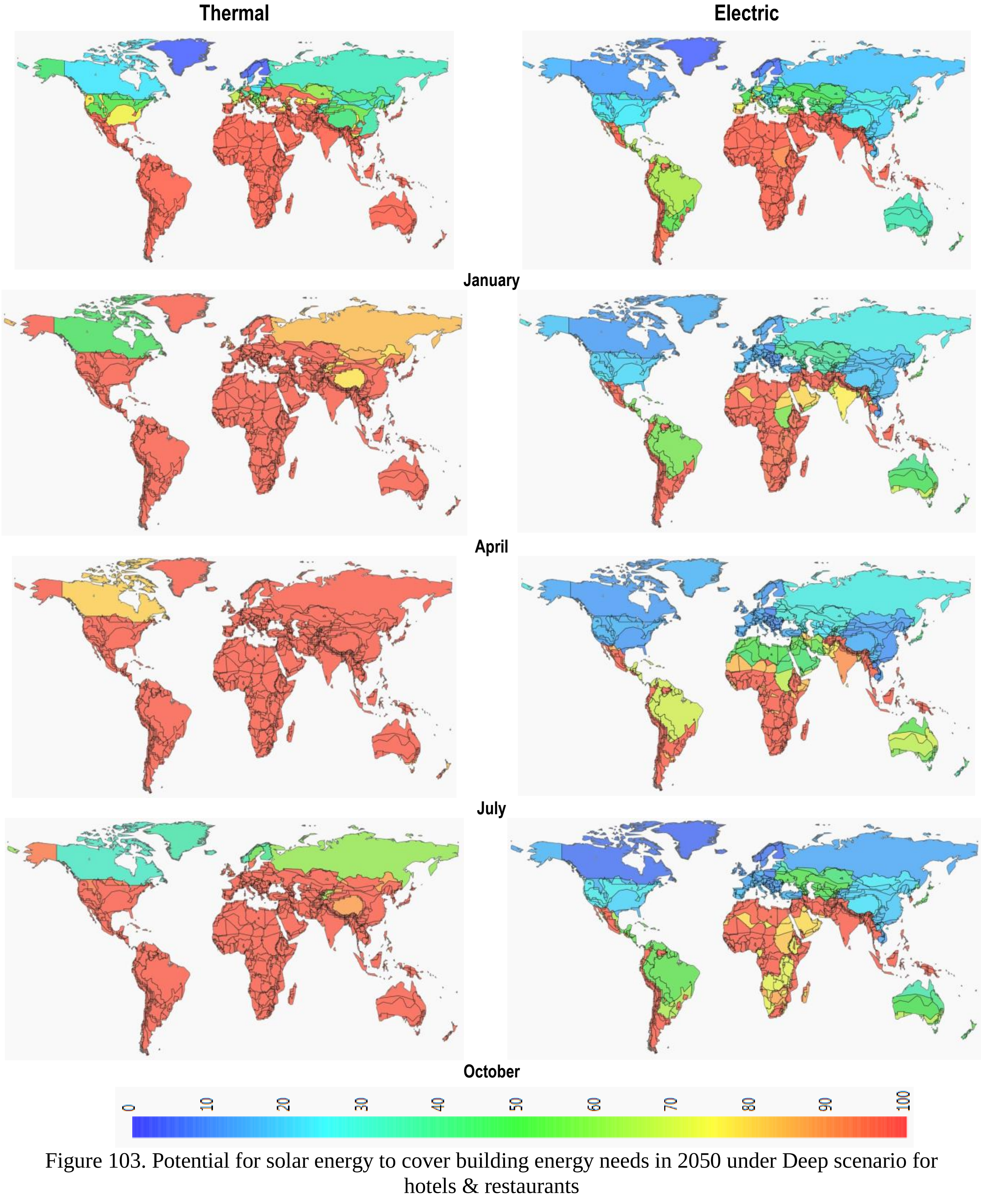


Figure 103. Potential for solar energy to cover building energy needs in 2050 under Deep scenario for hotels & restaurants

*Note*: the legend shows the share of energy use, which can be covered by solar energy production

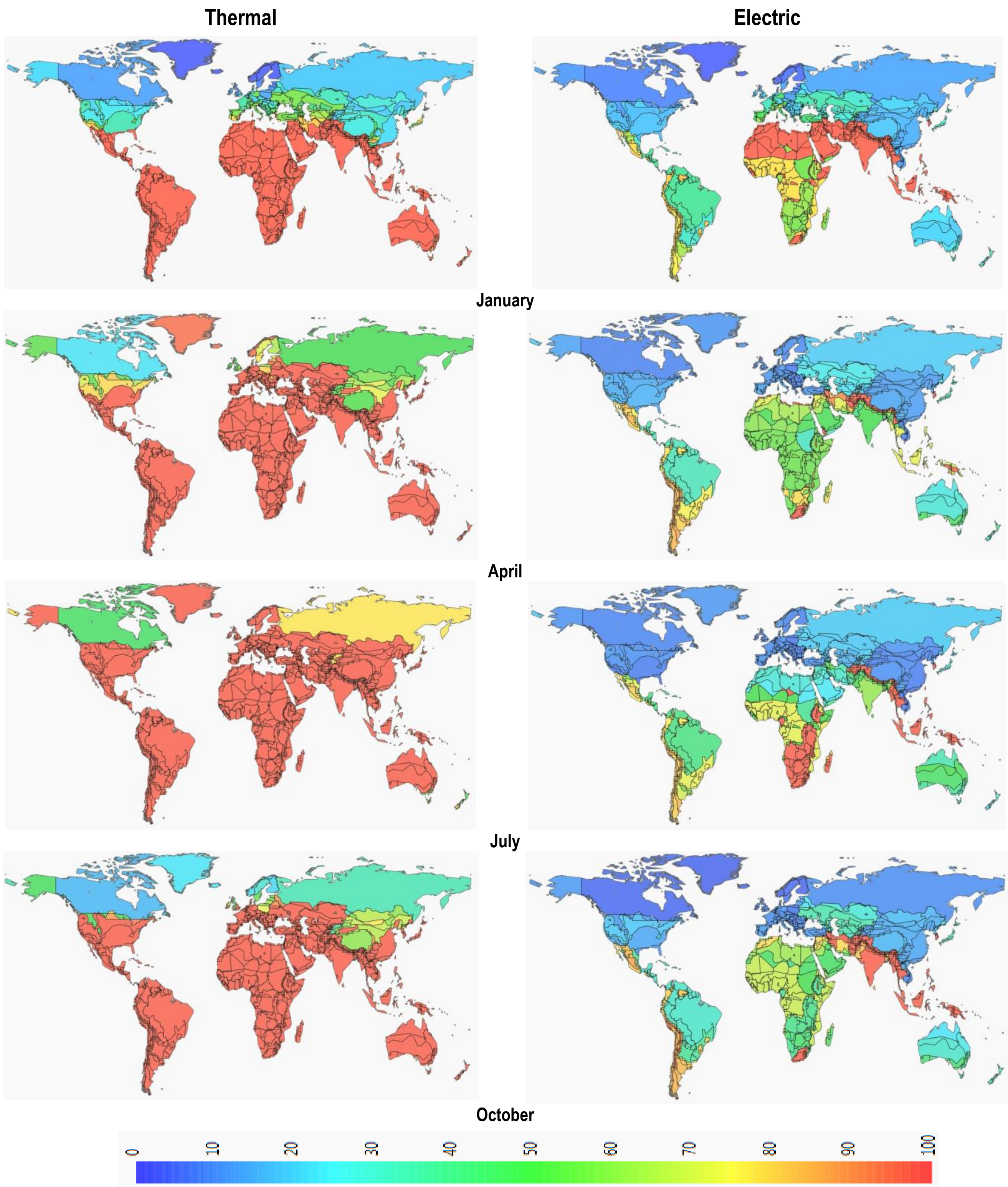


Figure 104. Potential for solar energy to cover building energy needs in 2050 under Deep scenario for hospitals

*Note*: the legend shows the share of energy use, which can be covered by solar energy production

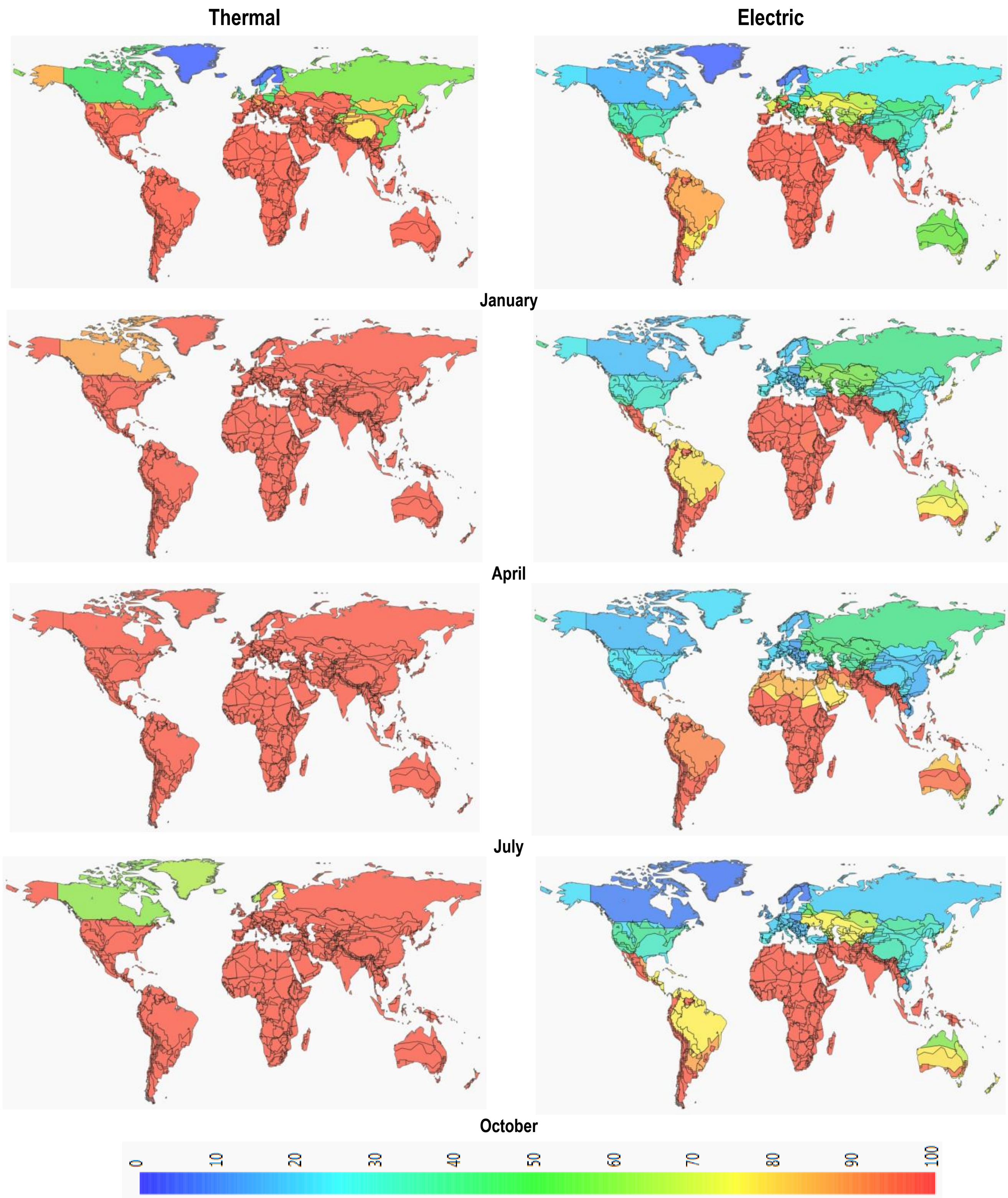


Figure 105. Potential for solar energy to cover building energy needs in 2050 under Deep scenario for retail buildings

*Note*: the legend shows the share of energy use, which can be covered by solar energy production

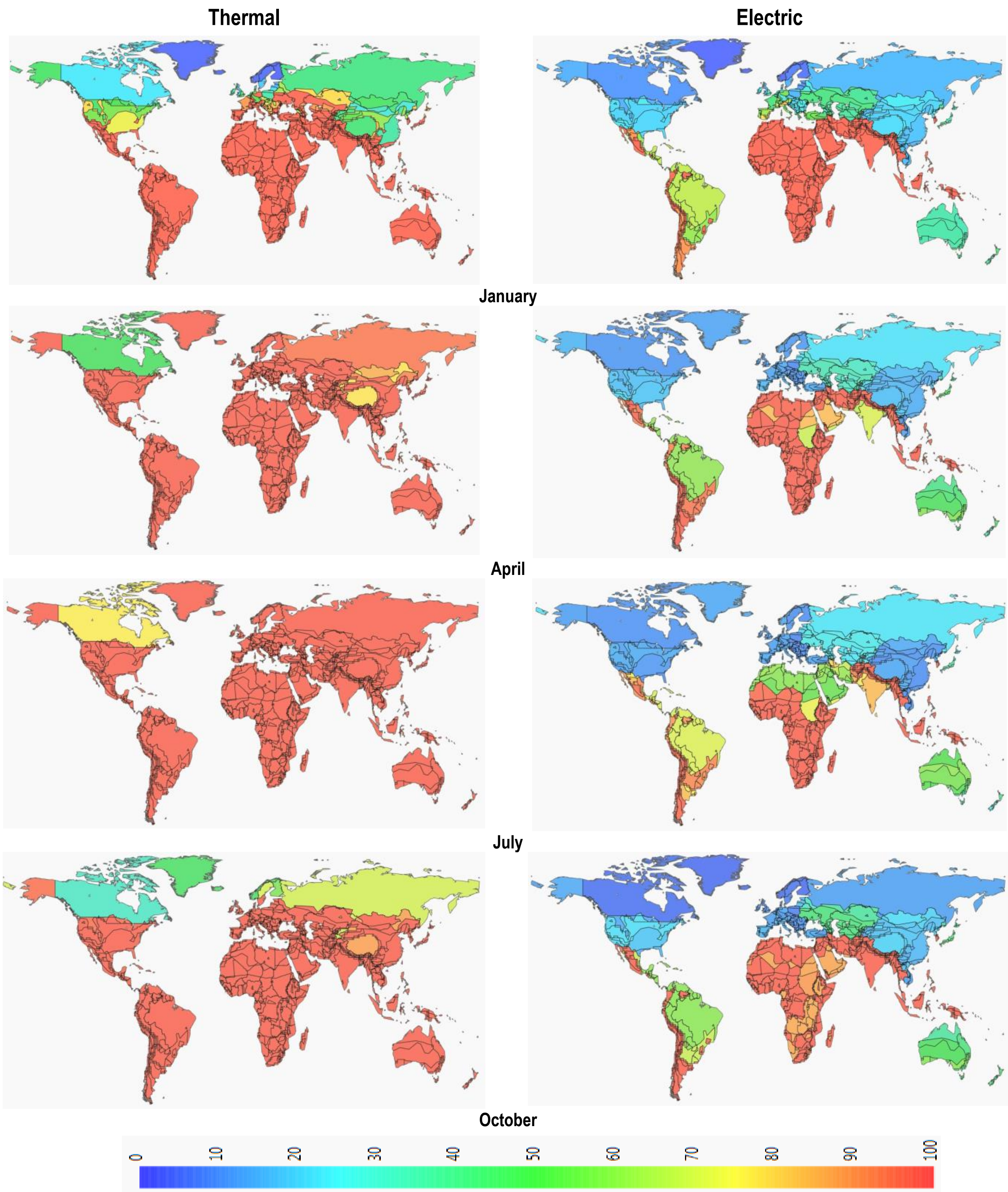


Figure 106. Potential for solar energy to cover building energy needs in 2050 under Deep scenario for other buildings

*Note*: the legend shows the share of energy use, which can be covered by solar energy production

# XVI ANNEX F. EXTERNAL LINKS

Links for the videos presented in Section VIII.10 on youtube.com are listed in Table 38.

Table 38. External links for the videos presented in this dissertation

| Name of the video | URL |
|---|---|
| Video 1. Potential for solar thermal energy to cover thermal energy needs in single-family buildings in 2015 under Deep scenario | http://youtu.be/LN4nVzbx1bk |
| Video 2. Potential for solar thermal energy to cover thermal energy needs in single-family buildings in 2050 under Deep scenario | http://youtu.be/jaVhw85BwuM |
| Video 317. Potential for solar electric energy to cover electric energy needs in single-family buildings in 2015 under Deep scenario | http://youtu.be/9MseWhh8_sk |
| Video 4. Potential for solar electric energy to cover electric energy needs in single-family buildings in 2050 under Deep scenario | http://youtu.be/jE2ErqTque4 |
| Video 5. Potential for solar thermal energy to cover thermal energy needs in multifamily buildings in 2015 under Deep scenario | http://youtu.be/tvOl63mxXQU |
| Video 6. Potential for solar thermal energy to cover thermal energy needs in multifamily buildings in 2050 under Deep scenario | http://youtu.be/3OuFPEA4HYM |
| Video 7. Potential for solar electric energy to cover electric energy needs in multifamily buildings in 2015 under Deep scenario | http://youtu.be/0GBAgdPl0vo |
| Video 8. Potential for solar electric energy to cover electric energy needs in multifamily buildings in 2050 under Deep scenario | http://youtu.be/2htNJ-OgyYY |
| Video 9. Potential for solar thermal energy to cover thermal energy needs in office buildings in 2015 under Deep scenario | http://youtu.be/obO_t897c6Q |
| Video 10. Potential for solar thermal energy to cover thermal energy needs in office buildings in 2050 under Deep scenario | http://youtu.be/NK8j65-I3ck |
| Video 11 Potential for solar electric energy to cover electric energy needs in office buildings in 2015 under Deep scenario | http://youtu.be/ZeG_fNYFCA4 |
| Video 12. Potential for solar electric energy to cover electric energy needs in office buildings in 2050 under Deep scenario | http://youtu.be/CuFYkn0aNn8 |
| Video 13. Potential for solar thermal energy to cover thermal energy needs in educational buildings in 2015 under Deep scenario | http://youtu.be/4HCwYkSx0uc |
| Video 14. Potential for solar thermal energy to cover thermal energy needs in educational buildings in 2050 under Deep scenario | http://youtu.be/3meD2KX7gHY |
| Video 15. Potential for solar electric energy to cover electric energy needs in educational buildings in 2015 under Deep scenario | http://youtu.be/SR_3bVooSVE |
| Video 16. Potential for solar electric energy to cover electric energy needs in educational buildings in 2050 under Deep scenario | http://youtu.be/CfoRjZuYJcc |