Available online at www.sciencedirect.com
ScienceDirect
Energy Procedia 57 (2014) 896 – 905
Energy Procedia

2013 ISES Solar World Congress

Assessing passive and active solar energy resources in cities using 3D city models

Ursula Eicker, Romain Nouvel, Eric Duminil, Volker Coors
University of Applied Sciences Stuttgart, Schellingstr. 24, 70174 Stuttgart, Germany, ursula.eicker@hft-stuttgart.de

Abstract

Many cities today are committed to increasing the energy efficiency of buildings and the fraction of renewables. However, quantitative data on urban energy performance are rarely available during the design stage of new towns or for rehabilitation scenarios of existing cities.

Three dimensional city models based on the spatio-semantic data format CityGML offer powerful new methods for the quantitative evaluation of urban energy demand and costs, and simultaneously allow the simulation of renewable energy systems. Such a 'semantically enriched' models was used in this work for energy demand diagnostics, refurbishment forecast and renewable supply scenarios.

A case study was done using this method in an existing urban quarter in Ludwigsburg/Germany. Based on its three dimensional representation, the photovoltaic potential has been calculated and compared with the electricity demand to establish the photovoltaic fraction. On the thermal side, the passive solar gains were simulated for each building in the city quarter to analyse the solar contribution for heating demand reduction. The simulations were validated with measured gas consumptions. Some rehabilitation scenarios have also been simulated. In such a moderately dense post-war district, the calculated energy savings potential reach in total 65%, equally distributed between heat savings following building envelope refurbishment, and electricity savings due to the installation of PV on the roofs.

Keywords: Urban energy simulation, 3D city model, CityGML, renewable integration

1. Introduction

With an increasing part of the human population living in urban areas, a rapid transition towards energy efficiency and renewable energy integration is required.

In this context, 3D city modeling can be an essential tool for energy planners and municipal managers, enabling them to make an accurate diagnostics of the existing building stocks, and to plan low-carbon urban energy strategies. These strategies consist in the coordination of building efficiency measures, the

doi:10.1016/j.egypro.2014.10.299

extension of sustainable energy supply concepts with a high renewable fraction, and the development of strategies for sustainable transport.

Every 3D city model approach aiming at simulating the energy demand of existing building stocks faces three main challenges: Firstly, taking into account the variety of the building data availability and levels of detail in existing urban areas with an appropriate data set standard. Then, developing a data pre-processing able to mitigate the lack of information by estimating the missing data and transforming the available one. Finally, establishing a heating demand calculation method adapted for a city scale purpose, offering a good compromise between low computation time and high result accuracy, while dealing with limited input requirement.

To address these issues, the two research centers Sustainable Energy and Geo-informatics of the University of Applied Sciences Stuttgart, have jointly developed an integrated energy demand and supply calculation process that is based on a CityGML city model. In this paper, this integrated process is described and tested on a case study: the city quarter Grünbühl in Ludwigsburg. The results and uncertainties are then analyzed and discussed. The parts 5 and 6 deal with energy saving potential calculations: heat savings following building refurbishment scenarios, as well as electricity savings following the use of photovoltaic modules on the roofs.

2. Urban energy analysis based on 3D city models

2.1. Three dimensional city modeling

The OGC Standard CityGML [1] has been chosen for the modelling of 3D building data in our integrated process. CityGML is an open multifunctional model which can be used for geospatial transactions, data storage, database modelling and provides a basis for 3D geospatial visualization, analysing, simulation and exploration tools. Thus, it offers the possibilities of numerous and miscellaneous spatial analyses like noise mapping, integration of new buildings in an urban surrounding, urban wind flow study, photovoltaic potential analyses, district network connections and extensions, heating demand calculation and simulation of refurbishment scenarios.

A considerable advantage of CityGML in comparison with other 3D city model formats such as X3D and KML is its spatio-semantic model, which specifies object modelling in different levels of detail. Due to this, it is an excellent data basis for heating demand analysis of existing building stocks, since the variety of data availability regarding the building parameters can be mirrored in the Levels of Detail of CityGML (see Figure 1). The most simple geometry representation of a building for the heating demand evaluation consists in a simple rectangular block. This block model consists in the "Level of Detail 1" (LoD1) of CityGML. The Level of Detail 2 (LoD2) adds the roof form to the building level, the Level of Detail 3 (LoD3) a detailed façade geometry including doors and windows, and the Level of Detail 4 (LoD4) the modelling of the indoor space.

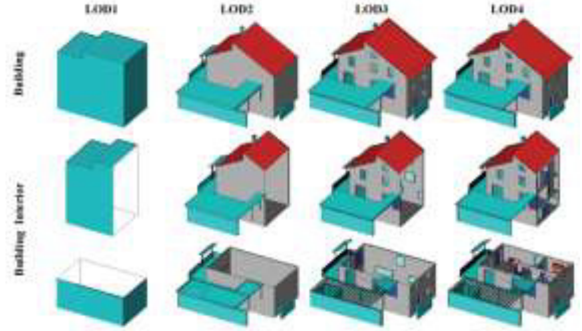

Figure 1 – The four Levels of Detail of CityGML (Groeger et al., 2012, page 72, Source: Karlsruhe Institute of Technology (KIT))

3D city model can be generated, either by stereo air photo, digital cadastre combined with building information (height, roof type), or laser scanning. In particular, this last technique allows an automatic generation of a CityGML model of whole cities in a short time. By 2013, the complete building stock of Germany will be modelled with CityGML – LoD1. Some federal states such as Baden-Württemberg will directly create a LoD2 model and derive the Lod1 models based on the LoD2 model on demand.

For the analysis of the CityGML-based 3D city model, the specific Java-based software SimStadtPreProc has been developed in the University of Applied Sciences Stuttgart, extracting relevant information like volumes, envelope surfaces and orientation, adjacent walls and buildings etc.. Furthermore, given the diverse qualities of 3D city models, the healing module "CityDoctor" has been integrated to the process, allowing to control and enhance the geometrical quality of the 3D model by closing polygons and volumes or separating buildings with common adjacent walls for instance [3].

2.2. Data pre-processing and enhancement

A systematic and automatic data pre-processing has been integrated in the process, allowing to calculate heating demands for different Levels of Detail and data availabilities. As the building´s thermal properties such as heat loss coefficients (U-values) are rarely known and their collection is time-consuming, some implemented algorithms assess them by using default values from building typology libraries. Depending on the availability of additional information, these values can be actualized, in particular with regard to refurbishment measures.

Such building typology libraries are essential to treat districts with several hundred/thousands buildings. They often exist at a national level [4], as well as for certain regions (the States Bavaria and Schleswig Holstein in Germany) and can be detailed for specific city quarters with exemplary monitoring projects (for example Karlsruhe Rintheim as a German nationally funded demonstration project). Generally, the more local these building libraries are defined, the higher is the accuracy of the on-site construction characteristics. As a result, this data pre-processing supplies formatted inputs to the heating demand calculation module.

2.3. Photovoltaic potential calculation

A Ruby plugin has been written in order to extract important attributes (ID, area, azimuth, tilt) for every roof. Additionally, a simulation model based on the software environment INSEL has been integrated into SketchUp/Ruby in order to calculate irradiance on tilted planes. Finally, some logic has been applied in order to determine the potential photovoltaic capacity for each roof:

A roof is eligible if

- its area is at least 20m² and
- it's almost flat (tilt lower than 10°) or if its azimuth lies between 75° (East, North=0°) and 285° (West).

If a roof is considered flat,

- the available area for photovoltaic panels is the roof area divided by 3.5 [12]
- Modules are oriented towards the south with an inclination of 30°

Otherwise:

- Modules are mounted to the roof, with the same tilt and azimuth
- The available area is 60% of the roof area [estimation from Google Maps/GeoBasis-DE/BKG], due to satellite dishes, windows or chimneys. This roof usage factor can eventually be precised, by analyzing in details some roof pictures (presence of chimney, roof windows etc.)

2.4. Heating demand calculation

Regarding the heating demand calculation, usual building performance simulation software tools are mostly not appropriate for a city scale calculation: they require too complex input data, are not designed to use geometry input from city models and to automatically generate parameter sets for the thermal properties, and have a programming and computation time, which is much too long. On the other hand, a purely statistical model, consisting in a multiplication of specific consumption ratios by the living area, does not use the potential of 3D city modelling for systematic parameter studies.

The monthly energy balance method (standardised in the ISO 13790) has been chosen as a reliable compromise in this integrated process. Its limited input requirements are compatible with a 3D city model, while its simplified mono-zone building physical model, worldwide used by the energy standard organisations, is robust and reasonably accurate. Moreover, the computing time of this heating demand calculation is well suitable to generate and compare long-term urban energy scenarios for districts with thousands of buildings.

An empirical “user-factor” depending on the thermal state of the building envelope [5] readjusts the standardised heating demand results especially for high consumption buildings. This user factor takes into account the fact that high energy bills often induce the tenant to only partially heat, to reduce temperature set-points and thus save energy.

The meteorological data used for the simulation are standardised regional monthly mean irradiances per façade orientation, as well as the monthly outside dry bulb temperature (DIN V 4108-6, annex A). The calculation algorithms are implemented in the software insel 8 (www.insel.eu).

Additionally to the heating demand diagnostics of the existing building stocks, refurbishment scenarios can be simulated., with different building energy standards equivalent to different envelope thermal efficiencies (U-Values of the building elements, airtightness, thermal bridges). Energy saving potentials as well as refurbishment investment costs are then calculated, taking into account the targeted building energy standards, the actual building thermal efficiency, and the building element areas from the 3D city model. These energy and economical indices will assist energy planners and municipal managers in the definition of the first refurbishment priorities, as well as in the development of a long-term urban energy strategy. This method has been already tested over several districts in Germany [6] and the Netherlands. This paper focuses on a case study district Grünbühl in Ludwigsburg.

3. Case study Grünbühl in Ludwigsburg

Grünbühl is a residential district in the South-East of Ludwigsburg (Germany), with a total living area of 80 000 m² on a ground area of 15 ha. During the research project EnEff:Stadt Ludwigsburg, a 3D city model has been built. Necessary geometrical data (ground floor area and mean building height measured by a laser scanning in 2002) and building attribute information (building usage, types, building and refurbishment years) were provided by the municipality of Ludwigsburg. Additional relevant data were collected on-site (window proportion per façade, possible outside insulation, basement configuration etc.). Thermal characteristics like U-values were taken from the national building typologies classification [7] and, for the refurbished buildings, updated with the onsite collection of data about building materials and insulation thickness.

Based on this 3D city model, heating demands per building block have been simulated. They are presented in kilowatt-hours per square meter per year, normalized by the reference heated area according to DIN V 18599-2 (2005).

The simulated heating demand per building in Grünbühl varies from 30 to 35 kWh/(m²a) for buildings fully refurbished in 2007, up to almost 200 kWh/(m²a) for post-war building blocks in very bad state (cracked walls, humidity damage, un-airtight roofs and windows). The mean heating demand in this residential post-war district reaches 106 kWh/(m²a).

Figure 2 – Simulated yearly heating demand, visualised in the 3D city model Grünbühl

To evaluate the accuracy of the model, simulated and real yearly heating demands have been compared per building blocks and for the whole district. The municipal energy company Stadtwerke Ludwigsburg, provided the mean gas consumption of the last 5 years for the different building blocks, adjusted with the degree-day method. From these data, the real heating demands have been calculated, using two assumptions: a gas boiler efficiency of 85% [8] and a domestic hot water (DHW) demand of 20 kWh/(m²a). As information concerning the heating systems inside the buildings was hard to obtain, particularly from the private owners, these assumptions of boiler efficiency and DHW demand must be considered with prudence. For instance, it is sometimes unclear if some individual apartments have electric or gas boilers for the DHW preparation.

The mean deviation between the simulated and real heating demands for the whole district reaches 18%, with a standard deviation of 11%. Detailed at a building block level, most of the individual simulated heating demands overestimate the real demand derived from measured consumption between 5 and 30%.

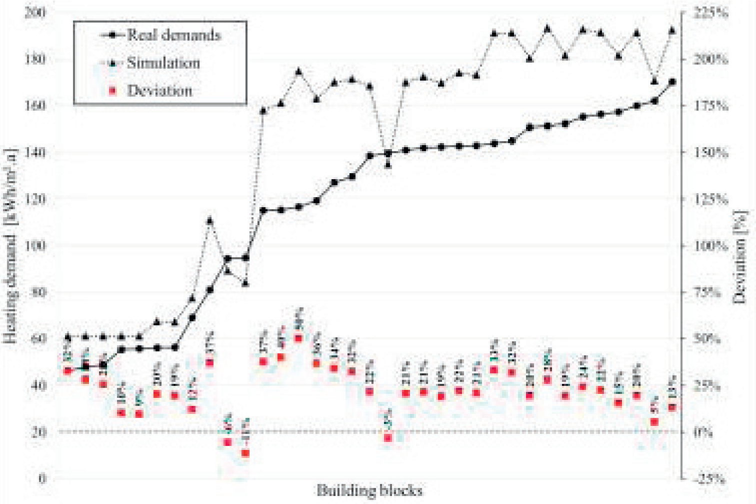

Figure 3 – Comparison simulated and real heating demand per building block in district Grünbühl

4. Influence of passive solar gains on heating demand

The heated volumes and areas are often higher in the calculation than in the reality, since information on basement floor height, staircase and other unheated zones are not available in most cases. Moreover, information data concerning window to façade ratios are often missing in 3D models of existing urban areas. For the case study Grünbühl, they have been roughly determined for each building during a laborious 2 days on-site survey. Alternatively, a ratio depending on the building typology is recommended in the case of a city model with thousands of buildings where an on-site survey would be too time-consuming.

Uncertainties on the window to façade ratios lead to errors on solar gains as well as on heat transmission losses, and as a consequence on the heating demand. Figure 4 represents the heating demand deviation relative to the window to façade ratio error in the case of the district Grünbühl. The considered interval of window to façade ratio corresponds to the typical range for residential buildings: 10% - 30%. The results of this sensitivity study have been detailed for the refurbished, the oldest buildings and the whole district. For each of these building groups, the heating demand deviations were calculated relative to the mean value of real window to façade ratios: 17% for the refurbished buildings, 18% for the oldest buildings and 20,3% for the whole district.

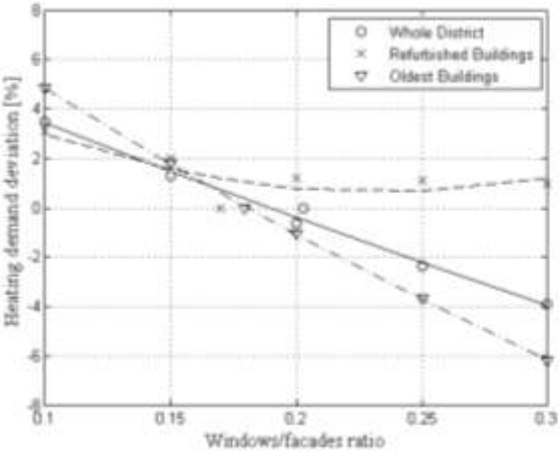

Figure 4 – Sensitivity study on window size

In the case of Grünbühl, the uncertainty on the window to façade ratio lead to a deviation smaller than +/-5% on the total heating demand.

Nevertheless, this result cannot be generalized to other case studies, since it is specific to the climate, the building main orientations, and the difference between the wall and the window U-values. For instance, most old buildings of Grünbühl have new windows whose U-values are not so far from those of the walls (respectively 1.6 and 1.4 W/(m²K)). When the window size is overestimated, the increase of solar gains overtakes the additional transmission losses, and leads to a lower heating demand. In another case study Karlsruhe Rintheim, the evolution of the heating demand following an increase of the window/wall proportion is opposite, even though it remains also under +/-5%.

5. Heating saving potentials and refurbishment priorities

In order to support the cities in their urban energy policies, and more precisely to define the refurbishment priorities, a mapping of the energy saving potential per building is particularly useful.

The energy saving potentials are obtained by the comparison of the existing heating demand, with a scenario, where all buildings are refurbished so as to reach a common energy standard.

The 3D mapping presented in Figure 7 shows the potential of heating demand savings in the district Grünbühl, which could be reached with a refurbishment of all building according to the German energy standard KfW-Effizienzhaus-85 [10]. This standard corresponds to a typical complete refurbishment with 10-15cm outside insulation (U=0.28 W/m^{2}K), roof (U=0.2 W/m^{2}K) and basement insulation (U=0.35 W/m^{2}K), and new double-glazed window with low emissivity coatings (U=1.3 W/m^{2}K).

Figure 5 – Heating energy saving potential, visualised in the 3D city model Grünbühl

In this case, the total heating energy saving potential reaches 64%. Most buildings achieve a saving potential over 60%, building blocks built in the 50's even reach saving potentials up to 75%. Buildings with saving potential under 20% correspond to already refurbished buildings.

Based on these saving potentials, a district-scale refurbishment strategy was simulated for the period 2010 until 2050. The refurbishment rate was set to 2% per year following the recommendation of the German Ministry for Environment. The priority was given to buildings with the highest energy saving potential.

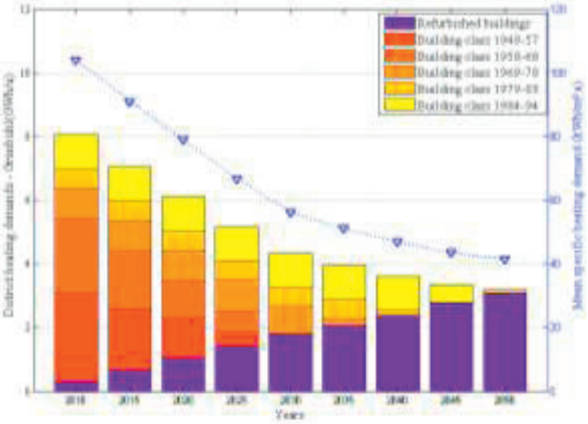

Figure 6 – Refurbishment scenario in Grünbühl over the period 2010-2050

With such urban refurbishment policy, the total heating demand of the residential district Grünbühl would be divided by 2 after 25 years, and would reach nearly 40 kWh/(m²a) in 2050 (compared to more than 100 kWh/(m²a) in 2010).

The 3D city model provides the different building envelope element areas, which are multiplied by the unit price (€/m²) of the different appropriated refurbishment measures (outside/inside insulation, exchange of the window, new ventilation systems etc…).

Figure 7 – Energy refurbishment costs, visualised in the 3D city model Grünbühl

6. Photovoltaic potential and electricity coverage ratio

The LoD2 CityGML model of Grünbühl has been imported into SketchUp. Some geometrical defaults created during the importation have been cleaned and coplanar faces have been merged. This way, it could be possible to install one large photovoltaic installation on different buildings sharing a common roof.

The photovoltaic installation is planned with 15% efficiency modules and is expected to have a performance ratio of 85%. Potential capacity is rounded down to the next integer if smaller than 15kW$_p$, and rounded down to the closest multiple of 5kW$_p$ for bigger installations.

The expected yield is obtained by multiplying the nominal power by the irradiance and the performance ratio.

Figure 8 - Potential PV yield. Green roofs could deliver more than 20 MWh/y

The global available roof area is 42 000 m², on which it would be possible to install about 17 000 m² of solar panels. The nominal capacity would be 2.3 MW_p for an approximate yield of 2.3GWh/a.

With an average electricity consumption per gross floor area of 29 kWh/m² [13] and a gross floor area of 120 000 m² (for both residential and non-residential buildings) the total consumption for Grünbühl alone is 3.54 GWh.

This means that approximately two third (65%) of the local electricity consumption could be covered by photovoltaic modules, from 130% for the most favorable building shapes, to 0% for some buildings without eligible roof surface for photovoltaics (PV).

The Figure 9 below shows for each building the potential PV electricity cover ratio in function of the shape index (quotient envelope area / volume), the area inside the circles being proportional to the PV electricity production.

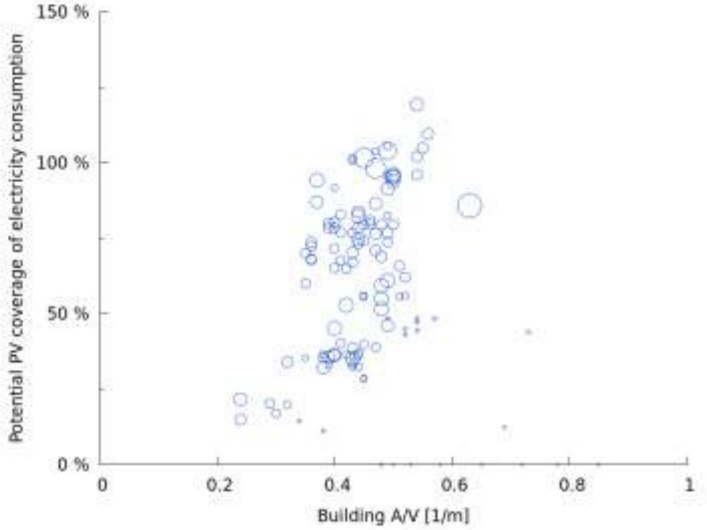

Figure 9 – PV Electricity cover ratio in function of the building shape index

A general tendency can be observed: the more compact the buildings, the lower is the potential PV electricity cover ratio. This is due to a smaller roof surface relative to the living area.

Thus, a high building compactness will in the same time optimize the heating demand (by the decrease of heat transmission losses) but limit the potential PV electricity cover ratio. In the other direction, a low building compactness is not the only criterium to get an optimized potential PV electricity cover ratio, as suitable roof surface orientations are also required. Furthermore the own consumption in less compact buildings is usually much lower than for compact buildings with smaller ratios of roof to living surface.

7. Conclusion

3D city models offer an excellent dataset for automatized and reliable heating demand diagnostics and renewable supply simulations.

If building physics information data are not directly available like in the presented case study, the use of local building typology libraries relative to building/refurbishment years allow to maintain a reasonable district heating demand error around 20%, but can lead for single buildings to higher uncertainties.

Further to this heating demand diagnostics, which serves as calibration phase, 3D city models offer opportunities to simulate energy scenarios, supporting city planners and municipal managers in the development of long-term urban energy strategies. The effect of each strategy can be measured with energy, environmental and economics indexes, supplying inputs to define for instance some refurbishment priorities, or to select the proftable roofs for photovoltaic installations.

In the case of the post-war residential district Grünbühl in Ludwigsburg, using a 3D City model showed that two third of the energy consumption (heating as electricity) could be saved with a ambitious energy strategy. Such a tool could play also an interesting communication role toward the population with its visualisation features.

Whatever their different applications, 3D city models have the potential to coordinate the whole city energy strategy and thereby beeing a key stone of the energy transition.

Acknowledgement

The authors would like to thank the city and the Stadtwerke Ludwigsburg for the fruitful long-term collaboration, as well as the German Ministry of Economy and Technology (BMWi) for funding the project EnEff:Stadt Ludwigsburg.

References

[1] Groeger, G., Kolbe, T.H., Nagel, C., Häfele, K.H. *OGC City Geography Markup Language (CityGML) En-coding Standard;* 2012. OGC Doc. No. OGC 12-019

[2] Gröger, Gerhard / Plümer, Lutz:CityGML - Interoperable semantic 3D City Models In: ISPRS Journal of Photogrammetry & Remote Sensing, 2012, Heft 71, S. 12-33 - online first - doi://10.1016/j.isprsjprs.2012.04.004

[3] Wagner, D.; Alam, N.; Coors, V. (2013): *Geometric validation of 3D city models based on standarized quality criteria*. In: C. Ellul, S. Zlatanova, M. Rumor und R. Laurini (Hg.): UDMS Annual 2013. Urban and Regional Data Management: CRC Pr I Llc, S. 197–210.

[4] European project Tabula. *Typology Approach for Building Stock Energy Assessment*. Web-site: http://www.building-typology.eu/tabula.html; May 2012

[5] Born R., Diefenbach N.. *Energieeinsparung durch Verbesserung des Wärmeschutzes und Modernisierung der Heizungsanlage für 31 Musterhäuser der Gebäudetypologie*. Institut Wohnen und Umwelt (IWU); 2002.

[6] Eicker, U., Nouvel, R., Schulte, C., Schumacher, J., Coors, V. *3D-Stadtmodelle für die Wärmebedarfberechnung*. Fourth German-Austrian IBPSA Conference, BauSIM2012; 2012

[7] Institut Wohnen und Umwelt (IWU). *Deutsche Gebäudetypologie, Systemik und Datensätze*. IWU Darmstadt; 2003

[8] Loga, T., Imkeller-Benjes, U. *Energiepaß Heizung/Warmwasser, Energetische Qualität von Baukörper und Heizungssystem*. Institut Wohnen und Umwelt (IWU); 1997.

[9] Felzenszwalb, P. F., Huttenlocher, D. P. *Efficient Graph-Based Image Segmentation*. International Journal of Computer Vision, Volume 59, Number 2, September 2004.

[10] EnEV 2009. *Energieeinsparverordnung 2009*. Annex 1 of the §3 and §9, table 1.

[11] Strzalka A., Alam N., Duminil E., Coors V., Eicker U. *Large scale ingretation of photovoltaics in cities*. Applied Energy 93. pp. 413-421; 2012.

[12] Falk A., Dürschner C., Remmers K., *Photovoltaics for Professionals - Solar Electric Systems: Marketing, Design and Installation.* Solarpraxis; 2006

[13] Bayerisches Staatsministerium für Umwelt und Gesundheit, *Leitfaden zur Erstellung eines Energienutzungsplanes*; 2011