Duet of solar energy and energy efficiency and its role for net zero energy buildings

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

Solar energy is often considered as the most widely available and accessible source for renewable energy supply generated on the building site, while energy efficiency is perceived as a necessary prerequisite for achieving net zero energy status of a building.

This paper aims at demonstrating the importance of the synergies between energy efficiency and solar energy in transition towards NZEBs on the global and regional levels. In order to achieve this goal both building energy demand and potential solar energy supply in buildings have been estimated in various regions, climate zones and building types.

Building energy demand has been analysed based on the bottom-up energy model, developed by 3CSEP and data inputs from BUENAS model under two scenarios with different levels of ambition in terms of energy efficiency. A comprehensive model has been developed in order to estimate the technical potential of advanced building-integrated hybrid (i.e. producing both solar electricity and heat from the same system's surface) solar energy 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 dynamic visualisation techniques.

The results of the analysis demonstrate that achievement of advanced energy efficiency levels is crucial for solar-supplied net zero energy buildings in a number of building types and regions. Energy efficiency significantly increases the share of building energy needs that can be met by solar energy. In a number of developing regions with abundance of solar energy, energy efficiency can not only help to achieve NZE status in certain building types, but also reduce the size of the solar systems and/or even make buildings energy exporters.

The paper advocates for the importance of policy actions, which package together energy efficiency and solar energy. It is particularly important for developing countries, which usually have significant solar energy resources available throughout the year, the potential of which often remains unrealized.

Introduction
One of the common definitions of a net-zero energy building, which can be found in the literature is the following: "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).

This definition implies that energy efficiency should be one of the strategies towards achieving net zero energy building performance. The necessity of energy efficiency strategies in NZEBs has been emphasized in a number of literature sources, for example: Torcellini, Pless, and Deru (2006), Pless and Torcellini (2010), Crawley, Pless, and Torcellini (2009), Laustsen (2008), Tse and Fung (2007), Carmichael and Managan (2013).

Crawley, Pless, and Torcellini (2009) emphasized the priority for energy efficiency in NZEB design and formulated the principle: "tackle demand first, then supply", which 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 use renewable energy sources to satisfy building's energy needs. Energy efficiency typically offers cost-effective strategies for energy demand reduction, which helps to reduce the size and, therefore, the cost of renewable energy systems needed, as well as accompanying embedded energy (Steven Winter Associates Inc 2014).

This paper aims at analysing synergies between energy efficiency and on-site solar energy supply for moving towards building net zero energy performance. The conclusions are drawn on the basis of Building Integrated Solar Energy (BISE) Model developed by the author and the data from two other well-known models in the field. This quantitative analysis has the goal to illustrate that energy efficiency and renewable energy supply are inseparable strategies and the insufficiency of either of them has aggravating impact on the potential to achieve net-zero energy balance in buildings.

Methodology

Energy modelling is widely used for the assessment of potential energy use and/or energy generation in different sectors. Two main types of models are usually discussed in the literature: top-down and bottom-up (IPCC 1996; Novikova 2010; Repetto and Austin 1997). Top-down models use aggregated macroeconomic data, including historical trends, to construct interactions between different sectors of the economy at the large-scale (IPCC 1996). Bottom-up models focus on the estimations based on the detailed technological and cost data of various sub-sectors, which together constitute the overall energy consumption for a country or sector of economy (Novikova 2010). While bottom-up models usually allow for receiving more detailed and precise results, the access and collection of disaggregated data required for such models, is often challenging and sometimes impossible task.

This paper presents the results from a global bottom-up model, which combines energy modelling of building energy use and on-site solar energy production with geospatial analysis, using a number of geographic information systems (GIS) techniques. GIS framework offers a wide variety of methods for collection, storage, retrieval and visual display of geographically referenced data (Fortheringham and Rogerson 1994). The main purpose of this modelling exercise is to calculate the hypothetical maximum possible technical potential of building-integrated solar energy to satisfy building energy needs and achieve net zero energy of building energy performance. The model assumes significant technological (and policy) advancements by 2025 in order to realise this solar energy potential.

The modelling exercise, the results of which are presented in this paper, consists of three main building blocks in accordance with different sources of data (see Table 1). While BISE model, developed by the author, is the main analytical product for the results presented in this paper, the other two building block only provide certain data needed to draw analytical conclusions and, therefore, described in much less details in this paper. The methodological details of these models can be obtained from the sources presented in Table 1.

BISE model estimates potential for building-integrated solar energy supply, which in combination with the results on building energy use from 3CSEP-HEB and BUENAS models, give the opportunity to draw the conclusions on how much of these energy needs can be satisfied with solar energy in different regions and building types.

3CSEP-HEB MODEL

3CSEP-HEB was developed by the research team (including the author of this paper) at Central European University with the aim to estimate the global building thermal energy use between 2005 and 2050 under several policy-driven scenarios. The core principle of the model is a performance-based approach for building energy use analysis, which considers a building as a holistic system rather than a set of independent technological components. Under this approach the main model's input data is specific final energy consumption of exemplary buildings (for each region, climate zone, building type, building vintage) per square meter of the floor area, which were collected by the research team through a number of various sources, which are documented in Urge-Vorsatz et al. (2012). These building's energy intensities are subsequently multiplied by respective building floor area estimation to calculate final energy consumption separately for space heating, space cooling and water heating across different regions, climate zones, building types and vintages. The floor area has a different calculation mechanism for residential and commercial buildings taking into account typical building processes, such as demolition, renovation and new construction, driven by population dynamics and changes in economic development.

Table 1. Building blocks of modeling exercise.

Part of modelling results	Building block	Source of data/results
Building final energy use for space heating, cooling and water heating	3CSEP-HEB model (Centre for Climate Change and Sustainable Energy Policy High Efficiency Buildings)	(Urge-Vorsatz et al. 2012; Urge-Vorsatz, Petrichenko, and Butcher 2011; Urge-Vorsatz et al. 2013)
Final energy used for lighting and appliances	BUENAS model (Bottom-Up Energy Analysis System model)	(McNeil et al. 2012; McNeil et al. 2013)
Solar energy generation from building-integrated technologies	BISE model (Building Integrated Solar Energy Model)	(Petrichenko 2014)

The model incorporates three scenarios, which presume different levels of policy efforts in the field of building energy efficiency and, consequently, different shares of energy efficient buildings in the regional building stocks:

- Deep Efficiency scenario presumes an ambitious proliferation of energy efficiency best-practices in buildings on world-wide scale. Building energy intensities are at the level of passive house energy performance (15–30 kWh/m^2 for space heating & cooling depending on the region).
- Moderate Efficiency scenario accounts for mediocre continuation of the existing policy trends and modest improvements in building energy efficiency in some developed regions. Building energy intensities are at the level of local building codes (100–200 kWh/m^2 for space heating & cooling depending on the region).
- Frozen Efficiency scenario assumes that current state of the building energy efficiency will remain unchanged throughout the analysed period without introduction of new policy instruments or technological improvements related to energy efficiency in buildings.

Deep scenario is primarily used for the analysis of the NZE potential as it presumes significant energy efficiency improvements, necessary for achieving the NZE goal. Results on the energy use from this scenario are further compared to the estimations on building integrated solar energy potential performed by BISE model, as described below. Results of the Moderate scenario are used in the same way to illustrate the impact of lower building envelope efficiency on the NZE potential.

BUENAS MODEL

BUENAS model provides the results for energy use for appliances and lighting in buildings in order, which together with the results of the thermal energy use from 3CSEP-HEB model allow for estimating the total building energy use.

> 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 is a bottom-up model, which provides the results for 11 countries and the European Union (EU-27) as one region, covering various energy-consuming products (except for electronics, such as TVs, computers, etc.) in residential, commercial and industrial sectors. The methodology for energy demand estimation in this model is based on three key parameters: activity (i.e. size of the stock of the units), intensity (i.e. usage and capacity of a unit) and efficiency (i.e. technological performance of a unit).

The model differentiates between two main scenarios: 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, while efficiency is "frozen" at the 2010 level. The BP Scenario is built on capturing potential impacts of regulations related to efficiency improvements, assuming that all countries achieve ambitious 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).

BISE MODEL

In order to evaluate what share of the energy demand (estimated through the results of 3CSEP-HEB and BUENAS models) can be met by building-integrated solar energy production a separate model (Building Integrated Solar Energy Model – BISE Model) has been developed by the author of this paper, which takes into account various geographical, architectural, morphological and climatic parameters by means of geospatial analysis.

The main aim of the BISE model is to analyse maximum possible technical potential and dynamics of solar energy (both solar heat and electricity) supplied by building-integrated hybrid solar technologies. For this purpose high-resolution very detailed climatic data was downloaded from the NASA depository (NASA 2012) for several key parameters (top-of-atmosphere irradiation, global irradiation, ambient temperature, wind speed, etc. – for more details see Petrichenko 2014).

The added value of the BISE model is to access high-resolution climatic data, process it through elaborated calculation algorithm, obtain the results for potential hourly solar thermal and electric output from one square meter of solar technologies and visualize the results. This solar energy output per square meter is extrapolated for each region, climate zone and building type through respective estimates of roof area available for the solar systems installation.

Available roof area is estimated through application of roof-to-floor ratios to respective floor area estimates from 3CSEP-HEB model and several availability factors, obtained from the literature (e.g. Izquierdo, Rodrigues, and Fueyo 2008), to account for shaded spaces and the spaces occupied by roof facilities. The roof-to-floor ratios are derived for each region and building type from the GIS datasets on global urban build-up areas developed by Jackson et al. (2010) and further processed by the author of this paper by means of the GIS spatial analysis and zonal statistics technique (for details, see Petrichenko 2014). 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).

As roof area estimations to a large extent use the floor area results of 3CSEP-HEB model as input data, the structure of BISE model is very similar to the one of the 3CSEP-HEB model in terms of regions, building types, climate zones, building vintages and modelling horizon. These aspects of the model are described in more details below.

Geographical coverage

In order to enable the linkage between the results of the BISE and 3CSEP models, the analysis is performed for the same regional division presented in Ürge-Vorsatz et al. (2012). These regions include: North America (NAM), Western Europe (WEU), Eastern Europe (EEU), Former Soviet Union (FSU), Middle East (MEA), Latin America and Caribbean (LAC), Sun-Saharan Africa (AFR), Centrally Planned Asia (CPA), South Asia (SAS), Pacific OECD (PAO), Other Pacific (PAS).

Timeframe

The original input GIS data were obtained for each hour of each year between 2001 and 2005 and five-year average was calculated for each hour. These aggregated data was used in the base 2005 year, which was chosen in the alignment with 3CSEP-HEB model. The model performs analysis for each month and each year between 2005 and 2050.

Energy end-uses

BISE model assumes that solar heat produced by PV/T systems can be used for water and space heating, while solar electricity – for space cooling, lighting and appliances.

Building types, building vintages, climate zones

BISE model distinguishes between various building types (residential: single-family, multifamily; commercial & public: office, educational, hotels & restaurants, hospitals, retail, other buildings.), vintages (existing, new, retrofit, advance new, advanced retrofit), climate zones (depending on combination of data for HDD, CDD and relative humidity), which are the same as in 3CSEP-HEB model (for details, see Ürge-Vorsatz et al. 2012).

Solar technologies

BISE model focuses specifically on building-integrated onsite solar energy systems. Typically, such technologies can be divided into two broad categories: solar thermal systems and photovoltaics (PVs). The former one produces heat, while the latter one generates electricity. As a building needs both of them, maximisation of solar energy generation on the building site may require installation of both types of systems. It may cause the "battle on the roof" (not enough space on the roof for both PV and solar collectors to satisfy energy needs) and lead to additional costs, esthetical issues and increase in embodied energy of the solar systems (Affolter et al. 2005). Although solutions for this problem already exist through combination of solar systems with other technologies (e.g. PV + heat pump), as this paper focuses only on solar energy, a photovoltaic/thermal hybrid solar system is considered as one of the possible 'fully solar' solutions to this problem.

A photovoltaic/thermal hybrid solar system (or PV/T system) 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). Moreover, such a hybrid installation increases the electrical efficiency of the system as extraction and utilization of heat reduces the temperature of the systems and, thereby, improves its performance (Tripanagnostopoulos et al. 2002). 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. As this paper focuses on the estimation of the maximum possible technical potential of solar energy in buildings, PV/T technology has been considered as the most optimal solution for the modelling exercise.

In order to calculate the hypothetical technical potential of building-integrated solar energy, it is assumed that PV/T technologies are installed on available roof areas during buildings' construction or renovation starting with a few pilot projects in 2014 and gradually increasing the number of installation until becoming a common practice for all retrofit and new buildings by 2025.

BISE model presumes modelling of thermal and electric solar energy outputs separately by using the same calculated hourly irradiation on one square meter of a solar system area, but different parameters and formulas for thermal and electric efficiency and different systems' losses (see "Calculation milestones").

Synergies between solar energy and energy efficiency in buildings

BISE model estimates the amount of solar energy (both thermal and electrical), which can be generated in buildings through operation of building-integrated PV/T technologies on the hourly basis, which are further aggregated for the monthly scale. The current version of the model assumes the storage of produced solar energy within one month at the level of each region, building type and climate zone, which enables the comparison of the monthly totals with monthly estimates of the building energy use under Deep scenario of the 3CSEP-HEB model for space heating, space cooling and water heating and with estimates from BUENAS model on lighting and appliances.

The BAU scenario of BUENAS model had to be used for this, as Best Technology scenario at the moment of conducting the analysis did not cover commercial buildings. Therefore, the assumption that approximately 50 % of energy savings due to improvements in energy efficiency in these end-uses will be achieved by 2050 was made. In order to derive monthly results for appliances and lighting it was assumed that the same amount of energy for these end-uses is consumed each month.

Monthly results calculated by BISE model for potential solar thermal energy supply were compared to building energy use estimates for space heating and water heating, while potential solar electrical output was compared to building energy use for space cooling, lighting and appliances. Such a comparison provides the ground to judge how far advanced energy efficient buildings with solar energy technologies can get on the way towards the NZE goal.

Calculation milestones

The uniqueness of BISE model is the combination of a very detailed calculation mechanism (appropriate for estimating the performance of an individual solar system) for hourly solar energy output per one square meter of a solar system's surface and global coverage of the results. The algorithm utilizes different types of solar radiation, taking into account the tilt of the system (assuming the optimal tilt), earth rotation, latitude, time of the year and position of the sun. The method presented here for calculating energy collected by one square meter of a solar system per hour was adapted from Duffie and Beckman (1991), RETScreen (2004a), RETScreen (2004b), Ibrahim et al. (2009).

The algorithm has several calculation milestones. First, the total roof area is calculated for each region, climate zone and building, which is subsequently reduced through the application of the availability factors.

Roof area for each region, climate zone and building type

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

where

RA roof area

FA floor area

RF_{ratio} roof-to-floor ratio

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

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

where

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

AvF_f availability factor to account for effects of shading

AvF_S availability factor to account for effects of roof facilities

Secondly, hourly solar radiation received by one square meter of the solar system surface is calculated taking into account different types of available solar radiation.

Hourly total solar radiation on the (tilted) plane of the solar array

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

where

I_T total solar radiation received by the solar system's surface

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

β the system's slope, depending on the latitude

I_B beam radiation

I_D diffuse radiation

I_{glob} global radiation

$\left(\frac{1 + \cos\beta}{2}\right)$ 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)

$\left(\frac{1 - \cos\beta}{2}\right)$ a view factor to the ground

ρ the portion of the global solar radiation reflected from the ground

Then, this parameter is used to calculate separately electric and thermal solar energy outputs by one square meter of a solar system per hour taking into account characteristics of the solar system, as well as ambient temperature, system's losses, etc. Standard formulas for electric and thermal efficiencies of individual solar systems have been used to obtain these results (for example, see Duffie and Beckman 1991).

Finally, the solar thermal and electric outputs per square meter are multiplied by the estimates for the roof area available for solar systems installations for each region, climate zone and building type. Hourly data for solar energy supply is then aggregated for each month of the year[1], assuming the possibility of the solar energy storage within one month, and compared to the monthly estimates for building energy use for respective end-uses (solar thermal output is compared to results for space and water heating, solar electric output – to the ones for cooling, lighting and appliances). The complete algorithm of the BISE model is significantly more complex and involves further calculations of a number of parameters mentioned in this paper. For further details it is recommended to refer to Petrichenko (2014).

Results

In order to illustrate the importance of energy efficiency for solar-supplied NZEBs under BISE model, the results for energy balances (i.e. solar energy supply versus building energy use) with two 3CSEP's scenarios were compared: Deep Efficiency and Moderate Efficiency Scenarios for each of 11 regions, climate zones and building types[2]. The main aim of such comparison is to analyse the impact of the level of energy efficiency improvement on the solar fraction (i.e. the portion of building energy use, which can be covered by solar energy output) in different regions and building types. As has been noted above Deep scenario presumes very ambitious energy efficiency improvements (approximately passive house level of energy performance), while Moderate scenario presumes conventional building energy performance, which can be achieved by 2050, if the current policy trends are continued without major changes. The results of the Deep scenario were combined with the estimates for the energy use of appliances and lighting from the BAU scenario of BUENAS model with 50 % reduction of their energy intensities by 2050 to illustrate potential energy efficiency improvements from these end-uses.

Table 2–Table 5 present summary of the results on meeting building energy needs with solar energy in 2050, taking into account monthly balances. 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 that developing regions have the potential to achieve the NZE performance during the larger number of months than in developed ones. The explanation can be twofold: lower energy demand in buildings in developing countries due to more limited access to modern energy services and much higher availability of solar energy resources than in developed countries, most of which are located in the Northern Hemisphere.

Table 2 and Table 3 show that in developing regions (SAS, PAS, MEA, LAC, AFR) the difference between the scenarios in case of energy use for space and water heating is insignificant. Under both scenarios in most of the building types (with few exceptions) in these regions energy needs for these end-uses can be potentially satisfied solely with solar heat supply throughout the year.

1. It is assumed that the level of solar radiation and main climatic parameters does not change during the analyzed period.

2. Frozen Efficiency scenario of 3CSEP model was not taken into account for this analysis as the purpose is to compare high and moderate levels of efficiency for in achieving NZE performance.

In developed regions full coverage across all the months of the year 2050 can be achieved only in certain, mainly low-rise building types (e.g. retail or single-family buildings). The most high-rise buildings, typically represented by multifamily and office buildings, demonstrate the lowest NZE potential among other building types in developed regions. Depending on the region the number of the months, in which solar thermal is not sufficient for satisfying thermal energy demand in these building types, varies from 3 to 8. 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. This can be explained by large availability of solar energy in this region during most of the year.

Results for the Moderate scenario (Table 3) 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, in which significant portion of building energy demand could be covered with solar energy during most of the months under the Deep scenario, in the Moderate scenario will have several months, when it is not possible. Only five building types of PAO, single-family buildings in CPA and retail buildings in WEU, demonstrate the possibility to cover thermal energy use with solar in all months under the Moderate scenario.

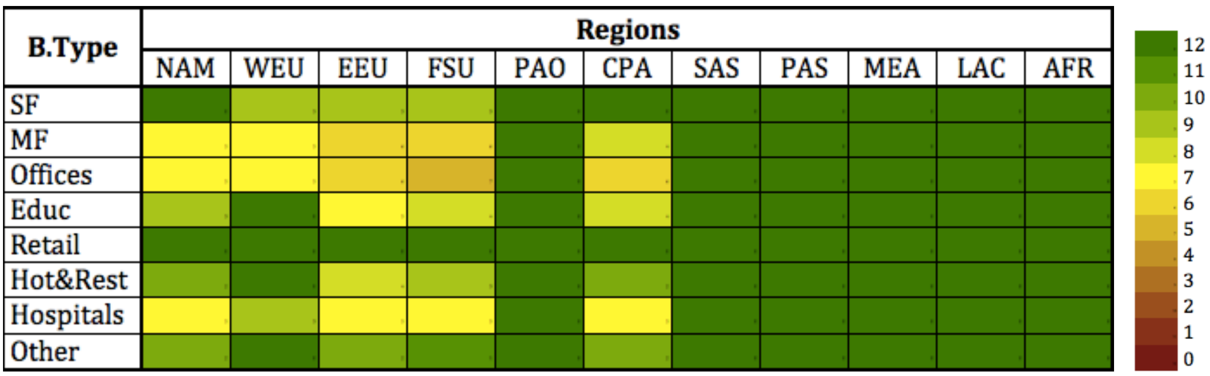
Developing regions have sufficient solar resources to cover thermal energy needs with solar heat throughout the year in the majority of the building types, even with the moderate levels of building energy efficiency. However, even in these regions in certain high-rise building types (e.g. office and hospital buildings in SAS, PAS and MEA, multifamily and educational buildings in MEA) it is challenging to maintain monthly zero-energy balances throughout the whole year.

As for electrical energy (Table 4 and Table 5) the difference between scenarios is more obvious in developing regions – the number of months, in which all electricity needs can be covered with solar energy is much larger in the Moderate scenario than that under the Deep one across almost all the regions and building types (exceptions are several building types in PAS and single-family buildings in LAC region, where full coverage has the potential during all the month of the year under both scenarios). Under the Deep scenarios developing regions demonstrate high chances to supply sufficient amounts of solar electricity to the majority of the building types. However, the results for two high-rise building types (multifamily and office buildings) in MEA and office buildings in LAC show that solar electricity will not be sufficient to cover building electricity needs during all the months of the year.

Putting thermal and electric results together give an idea, in which regions and building types it is possible to achieve NZE performance solely with solar energy based on monthly energy balances of 2050. Such cases include:

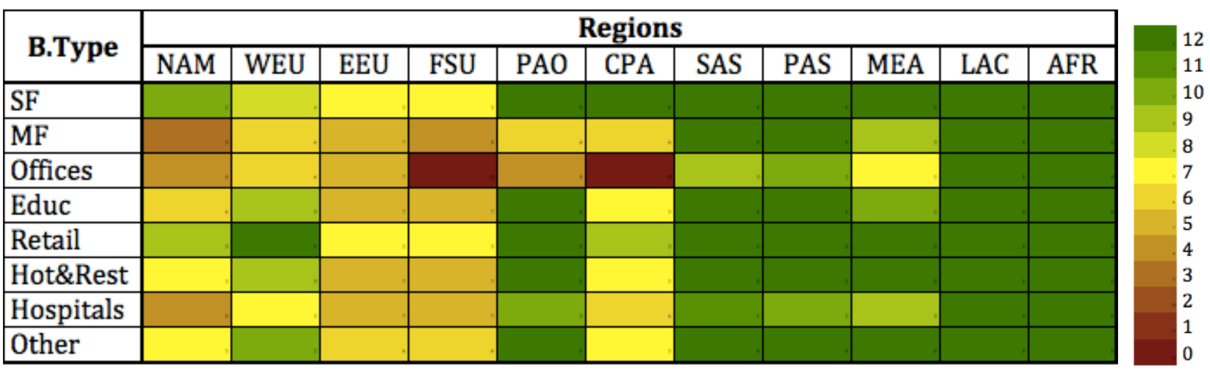
- All building types in PAS;
- Single-family buildings in PAO, SAS, EEU, CPA, MEA, LAC, AFR;

Table 2. Meeting thermal energy use needs by solar thermal energy in 2050, Deep scenario.



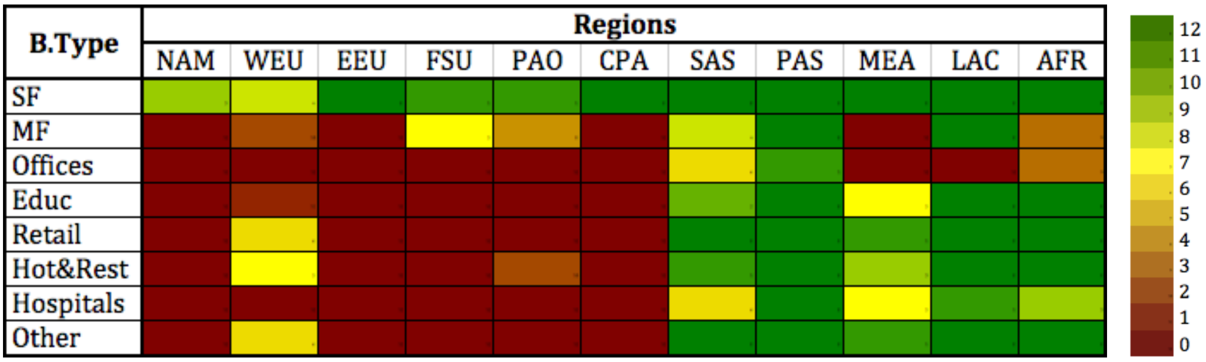
Different colors show number of months during the year 2050, in which energy use is covered by solar energy supply.

Table 3. Meeting thermal energy use by solar thermal energy in 2050, Moderate scenario.



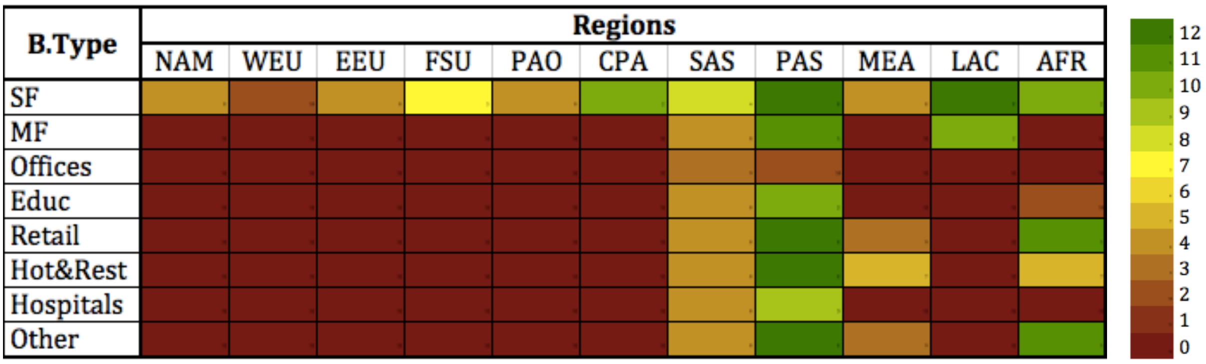
Different colors show number of months during the year 2050, in which energy use is covered by solar energy supply.

Table 4. Meeting electric energy use needs by solar electric energy in 2050, Deep scenario.



Different colours show number of months during the year 2050, in which energy use is covered by solar energy supply.

Table 5. Meeting electric energy use needs by solar electric energy in 2050, Moderate scenario.



Different colours show number of months during the year 2050, in which energy use is covered by solar energy supply.

- Retail buildings in SAS, LAC, AFR;
- 'Other' buildings in SAS, MEA, LAC and AFR;
- Educational buildings and hotels & restaurants in LAC and AFR;
- Multifamily buildings in LAC.

As can be seen, multifamily buildings show the potential to get closer to NZEBs only in two regions under the Deep scenario, while offices have a significant potential only in one region. On one hand, it can be explained by the fact that these building types consist of the tallest buildings on average, in which the roof area is quite limited in relation to the floor area and the respective energy demand. On the other hand, electricity needs in these buildings are significant. In office buildings (and other commercial types) lighting has a large share in the total building energy demand; while in multifamily appliances have a considerable contribution. Therefore, energy efficiency of lighting and appliances is crucial for NZEBs, especially in developing regions. Increase in efficiency of these end-uses can significantly increase solar fraction in most of the building types and regions. Therefore, strict product standards for various appliances and regulations for lighting systems are very important in this regard.

In order to deepen the understanding of the differences between Deep and Moderate scenarios and further illustrate the importance of energy efficiency for NZEBs the results on building energy use and solar energy supply for every month are presented in charts for each region (see Figure 1–Figure 4). Figure 1 and Figure 2 compare results for thermal energy use and solar thermal energy production under the Deep and Moderate scenarios for single-family and commercial & public buildings respectively, while Figure 3 and Figure 4 show the same type of the results for electric energy use versus solar electricity.

The figures clearly show the importance of energy efficiency for net-zero energy buildings: both thermal and electric energy uses are significantly higher under Moderate scenario than under the Deep one across all regions and building types. The higher the energy needs, the more challenging it is to satisfy them solely with building-integrated solar energy. It is particularly critical in developed regions, which have relatively low availability of solar resources and higher energy consumption. Figure 1–Figure 2 show that under the Moderate scenario thermal energy needs are much higher, especially in developed regions and particularly during the cold season, when the heating demand increases. Results for WEU, EEU, FSU, NAM show that under the Moderate scenario even in single-family buildings it is not possible to cover all thermal energy needs with solar energy during winter months, while energy efficiency improvements presumed by the Deep scenario significantly increase this potential. In commercial & public the need for space heating from the sources other than solar is even higher under the Moderate scenario and, therefore, higher levels of energy efficiency for space and water heating equipment as well as insulation, airtightness and other passive house measures (see Feist 2009) are crucial.

In developing regions larger thermal energy use might mean that less thermal solar 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 and overproduction in very sunny locations. 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 are based on BUENAS BAU estimates) and during hot season.

The results show that under the Moderate scenario the need for supplementary energy sources is much larger than under the Deep scenario. These energy sources are likely to use fossil fuels and, therefore, result in greater amount of GHG emissions. Therefore, the overall conclusion is that energy efficiency of all systems and end-uses, related to both building shell and plug loads, should be maximized in order to move towards NZEBs and ensure sufficient renewable energy supply for each month. Lower energy demand can also reduce the size of building-integrated renewable energy systems, which will allow for decreasing the investment costs and the amount of embedded energy related to the production of such technologies.

Conclusion

This paper has presented the results of the recent modelling exercise aimed at contributing to the discussion on feasibility of net-zero energy buildings in different regions, climate zones and building types. The paper has provided a brief description of the novel methodology based on bottom-up energy modelling and geospatial analysis integrated into one analytical model (BISE model).

The results presented in this paper consist of estimations for (1) future building energy use by 2050 for different regions, building types and end-uses and (2) maximum possible technical potential for solar energy generation from building-integrated technologies.

The main idea of this paper was to compare the results of the building energy use under two scenarios with different levels of building energy efficiency to the amount of solar energy, which can be potentially generated from these buildings' rooftops by hybrid advanced technologies. Although the calculations for solar energy potential have been performed for each hour, the comparison between solar energy supply and building energy use is done on the monthly basis (due to the lack of more detailed data on building energy use for the global and regional levels. It is assumed that generated solar energy can be stored on building site within one month at the level of each region, building type and climate zone.

The results of such comparison can be summarised in five key messages:

1. Synergies between energy efficiency and on-site solar energy generation play a crucial role in moving building energy performance towards net-zero energy level.
2. Through 'deep' energy efficiency measures the same amount of solar energy can satisfy a larger portion of the energy demand, reducing the need for additional energy supply from fossil fuels, and, therefore, accompanying greenhouse gas emissions.
3. In order to maximise the potential for net-zero energy performance efficiency of all building systems should be improved, including lighting and appliances. Thermal energy performance of new and retrofit buildings needs to reach the passive house levels (c.a. 15–30 kWh/m^2 depending on the location and building type). As for lighting and appliances, even halving their electricity use by 2050 will not be sufficient to enable full solar coverage of respective electricity needs in a number of regions (especially developed ones).

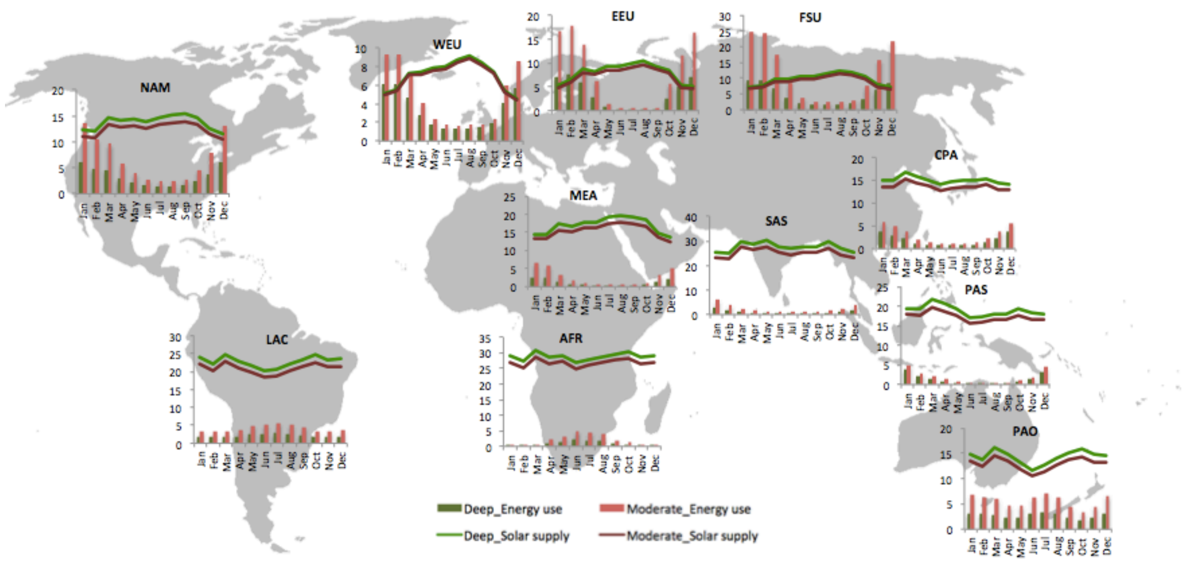


Figure 1. Thermal energy use vs. solar thermal energy production for single-family buildings in 2050, kWh/m^2 of floor area, Deep vs. Moderate scenarios.

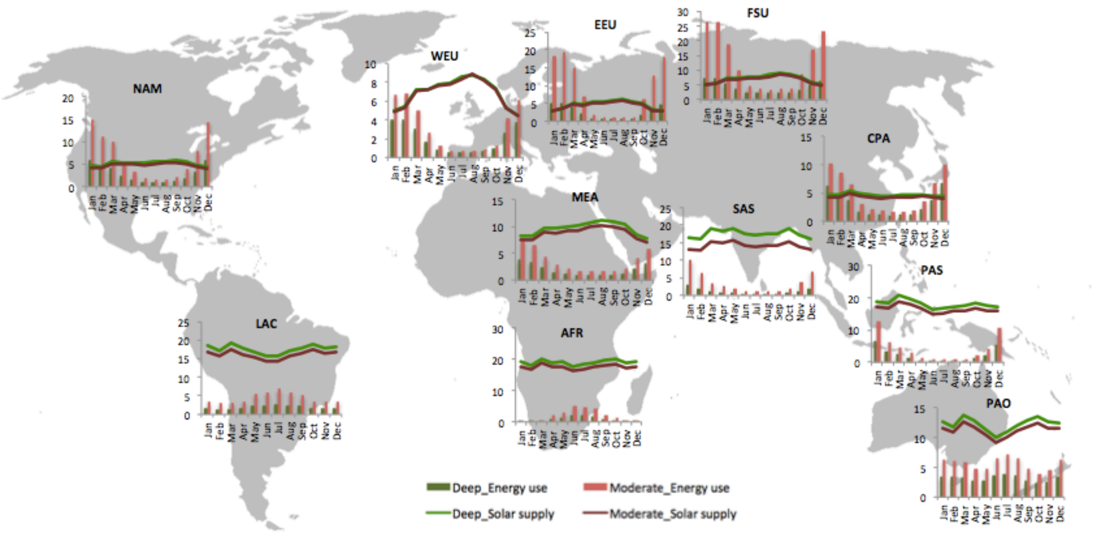


Figure 2. Thermal energy use vs. solar thermal energy production for commercial & public buildings in 2050, kWh/m² of floor area, Deep vs. Moderate scenarios.

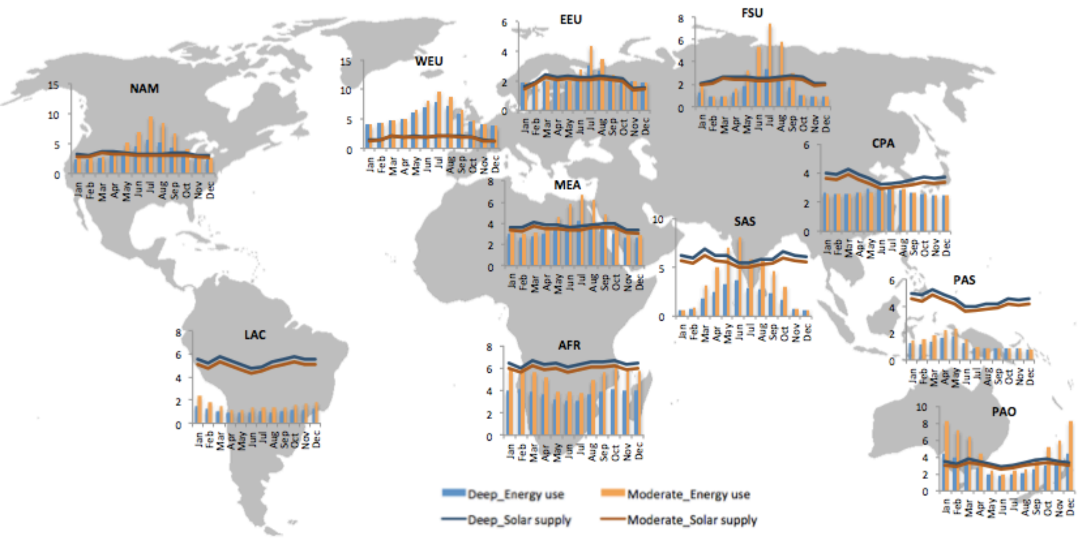


Figure 3. Electric energy use vs. solar electric energy production for single-family buildings in 2050, kWh/m² of floor area, Deep vs. Moderate scenarios.

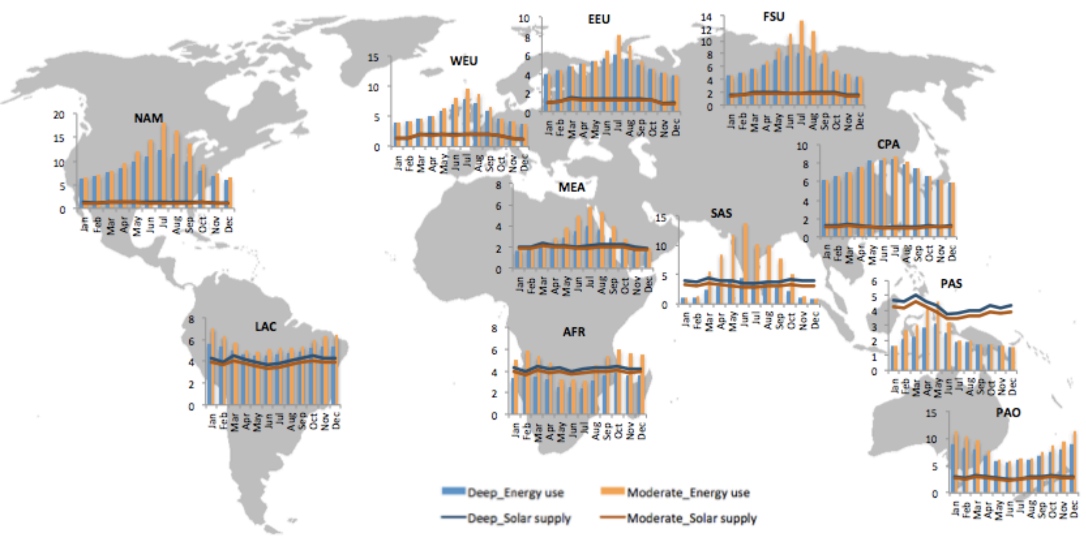


Figure 4. Electric energy use vs. solar electric energy production for C&P buildings in 2050, kWh/m² of floor area, Deep vs. Moderate scenarios.

4. Developing countries demonstrate higher solar energy potential in buildings due to abundance of solar energy resources and lower energy needs. In these regions, however, energy efficiency is also crucial in order to mitigate the rapid growth in energy consumption expected in these regions in the near future
5. Low-rise buildings typically demonstrate higher potential to cover substantial portion of their energy demand with solar energy than the high-rise ones. However, moderate levels energy efficiency makes the achievement of NZE goal more challenging in most of the building types.

The scope of the analysis was limited to the onsite rooftop solar systems, able to produce both solar electricity and heat (i.e. hybrid PV/Ts), however, in further research efforts it would be important to explore alternative options of renewable energy supply, for example, offsite solar generation, side by side installation of PV and solar thermal systems, combination of PVs with heat pumps, other types of renewables. Integration of the hourly data on building energy use can substantially improve the assumption on the storage of solar energy and accuracy of the results. Another limitation of the analysis is that it does not explore potential costs of solar technologies for realisation of the solar energy and energy efficiency potentials. Analysis of the economic potential would be a very important direction of the further research. The BISE model does not take into account potential effects of climate change by 2050 on the amount of solar radiation, wind speed, ambient temperature. For more accurate results in the next versions of the BISE model it would be important to integrate some assumptions of the existing climate scenarios in order to capture future climate and weather change patterns.

References

Affolter, P, W Eisenmann, H Fechner, M Rommel, A Schaap, H Sørensen, Y Tripanagnostopoulos, and H Zondag. 2005. *PVT ROADMAP. A European Guide for the Development and Market Introduction of PV-Thermal Technology*. EU-supported Coordination Action PV-Catapult. www.pvtforum.org.

Câmara, G, A Monteiro, S Druck Fucks, and M Sá Carvalho. 2008. *Spatial Analysis and GIS: A Primer*. Brazil: Image Processing Division, National Institute for Space Research; Brazilian Agricultural Research Agency; National School for Public Health.

Carmichael, C, and K Managan. 2013. *Reinventing Existing Buildings: Eight Steps to Net Zero Energy*. Rocky Mountain Institute, Johnson Controls. http://www.institutebe.com/InstituteBE/media/Library/Resources/Green%20Buildings/Reinventing-Existing-Buildings-8-Steps-to-Net-Zero-Energy_JCI-RMI.pdf.

Crawley, D, S Pless, and P Torcellini. 2009. "Getting to Net Zero." *ASHRAE Journal*, NREL/JA-550-46382, September 2009.

Duffie, J.A, and W.A Beckman. 1991. *Solar Engineering of Thermal Processes*. 2nd Edition. John Wiley & Sons.

Dupeyrat, P, C Ménézo, M Rommel, and H Henning. 2011. "Efficient Single Glazed Flat Plate Photovoltaic–thermal Hybrid Collector for Domestic Hot Water System." *Solar Energy* 85 (7): 1457–68. doi:10.1016/j.solener.2011.04.002.

Feist, W. 2009. *Cost-Efficient Passive Houses in a Central European Climate*. Passive House Institute. www.passivehouse.com.

Fortheringham, S, and P Rogerson, eds. 1994. *Spatial Analysis and GIS*. Technical Issues in Geographic Information Sysytems. Great Britain, London: Taylor & Francis Ltd.

Ibrahim, A, M.Y Othman, M.H Ruslan, M.A Alghoul, M Yahya, A Zaharim, and K Sopian. 2009. "Performance of Photovoltaic Thermal Collector (PVT) With Different Absorbers Design." *WSEAS TRANSACTIONS on ENVIRONMENT and DEVELOPMENT* 5 (3).

IPCC. 1996. *Climate Change 1995: Economic and Social Dimensions of Climate Change*. Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Intergovernmental Panel on Climate Change (IPCC). http://www.ipcc.ch/ipccreports/sar/wg_III/ipcc_sar_wg_III_full_report.pdf.

Iqbal, M. T. 2004. "A Feasibility Study of a Zero Energy Home in Newfoundland." *Renewable Energy* 29 (2): 277–89. DOI: 10.1016/S0960-1481(03)00192-7.

Izquierdo, S, M Rodrigues, and N Fueyo. 2008. "A Method for Estimating the Geographical Distribution of the Available Roof Surface Area for Large-Scale Photovoltaic Energy-Potential Evaluations." *Solar Energy* 82 (2008): 929–39.

Jackson, T.L, J.J Feddema, K.W Oleson, G.B Bonan, and J.T Bauer. 2010. "Parameterization Od Urban Characteristics for Global Climate Modeling." *Annals of the Association of American Geographers* 100 (4): 848–65.

Laustsen, J. 2008. *Energy Efficiency Requirements in Building Codes, Energy Efficiency Policies for New Buildings.* IEA Information Paper. Paris Cedex, France: International Energy Agency.

McNeil, M, V.E Letschert, S de la Rue du Can, and J Ke. 2012. *Bottom-Up Energy Analysis System – Methodology and Results*. In Partnership with The Collaborative Labeling and Appliance Standards Program (CLASP). Berkeley, CA, US: Lawrence Berkeley National Laboratory.

—. 2013. "Bottom–Up Energy Analysis System (BUENAS) – an International Appliance Efficiency Policy Tool." *Energy Efficiency*, in Partnership with The Collaborative Labeling and Appliance Standards Program (CLASP), 5 (4).

NASA. 2012. "MDISC Data Subset." Goddard Earth Sciences Data and Information Services Center. http://disc.sci.gsfc.nasa.gov/daac-bin/FTPSubset.pl.

Novikova, A. 2010. *Methodologies for Assessment of Building's Energy Efficiency and Conservation: A Policy-Maker View*. Berlin, Germany: Deutsches Institut für Wirtschaftsforschung (DIW).

Oke, T.R. 1987. *Boundary Layer Climates*. 2nd ed. London, New York: Methuen.

Petrichenko, K. 2014. "Net-Zero Energy Buildings: Global and Regional Perspectives." Doctoral dissertation, Budapest, Hungary: Central European University.

Pless, S, and P Torcellini. 2010. *Net-Zero Energy Buildings: A Classification System Based on Renewable Energy Supply Options*. Technical Report NREL/TP-550-44586. Taks Nos. BEC7.1210, BEC7.1123. Colorado, US: National Renewable Energy Laboratory (NREL).

Repetto, R, and D Austin. 1997. *The Cost of Climate Protection: A Guide for the Perplexed*. Climate Protection Initiative. Washington, DC, US: World Resources Institute. http://pdf.wri.org/costsclimateprotection_bw.pdf.

RETScreen. 2004a. "Solar Water Heating Project Analysis Chapter." In *Clean Energy Project Analysis*, Third edition. RETScreen® Engineering & Cases Textbook. Canada: Minister of Natural Resources Canada. www.retscreen.net.

—. 2004b. "Photovoltaic Project Analysis Chapter." In *Clean Energy Project Analysis*, Third edition. RETScreen® Engineering & Cases Textbook. Canada: Minister of Natural Resources Canada. www.retscreen.net.

Steven Winter Associates Inc. 2014. "Net Zero Energy Buildings." *Whole Building Design Guide*. December 16. http://www.wbdg.org/resources/netzeroenergybuildings.php.

Torcellini, P, S Pless, and M Deru,. 2006. "Zero Energy Buildings: A Critical Look at the Definition." In . NREL/CP-550-39833. USA: National Renewable Energy Laboratory (NREL).

Tripanagnostopoulos, Y, M Souliotis, R Battisti, and A Corrado. 2002. "Application Aspects of Hubrid PV/T Solar Systems."

Tse, H., and A.S. Fung. 2007. "Feasibility of Low-Rise Net-Zero Energy Houses for Toronto." In . Calgary, Canada.

Ürge-Vorsatz, Diana, Nick Eyre, Peter Graham, Danny Harvey, Edgar Hertwich, Yi Jiang, Christian Kornevall, et al. 2012. "Chapter 10 – Energy End-Use: Building." In *Global Energy Assessment – Toward a Sustainable Future*, 649–760. Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria. www.globalenergyassessment.org.

Urge-Vorsatz, D., K Petrichenko, M Antal, and M Staniec. 2013. "Cutting the Energy Use of Buildings: How Deep Can the Planet Go?" In *Rethink, Renew, Restart*. Vol. 1543–1553. Club Belambra Les Criques, Presqu'île de Giens, Toulon/Hyères, France.

Urge-Vorsatz, D., K Petrichenko, M Antal, M Staniec, M Labelle, E Ozden, and E Labzina. 2012. *Best Practice Policies for Low Energy and Carbon Buildings. A Scenario Analysis*. Budapest, Hungary: Research report prepared by the Center for Climate Change and Sustainable Policy (3CSEP) for the Global Best Practice Network for Buildings. http://www.globalbuildings.org/global-projects/.

Urge-Vorsatz, D., K Petrichenko, and A Butcher. 2011. "How Far Can Buildings Take Us in Solving Climate Change? A Novel Approach to Building Energy and Related Emission Forecasting." In *Energy Efficiency First: The Foundation of a Low-Carbon Society*. Belambra Presqu'île de Giens, France. http://proceedings.eceee.org/.

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