Building Integrated Photovoltaics to achieve Net Zero Energy Buildings: a review

Alice Hartog
Utrecht University
Faculty of Geosciences
Utrecht, The Netherlands
a.hartog1@students.uu.nl

***Abstract*—Around 1/3 of the global energy consumption comes from buildings. For this reason, a lot of research addresses the built environment aiming at the construction of nearly Net Zero Energy Buildings (NZEBs), buildings with an almost optimal energy performance, whose available energy for consumption comes from renewable sources, to slowly reach the Net Zero Carbon Emissions goal [1]. The main idea with these types of buildings is not necessarily to save energy but to balance annual in- and outcome of energy without using fossil fuels.**

The evaluation of energy demand and its load match in a household are crucial in developing these buildings. Among all the on-site production technologies, Building Integrated Photovoltaics (BIPV) are the most advantageous electricity generators because of their perfect integration within the building.

Since buildings construction is increasing and this trend will continue at the same pace in the coming years, the integration of BIPVs could be the key to develop NZEBs and thus solve the main energy consumption issue at least in residential areas, where the available space is not sufficient to allow other renewable technologies to produce clean energy. The significant aspect regarding this integration is not only the development of NZEBs, but also how they can be energy efficient and consequently have a lower impact on the energy system costs comprised in a household.

This paper gives an overview on the main most recent studies regarding BIPVs integration for NZEBs development, through the analysis of several research papers written on this topic, to show how much this system is important and contributes to an increase in both energy efficiency and cost savings in a household.

Keywords: Building Integrated Photovoltaics, Net-Zero Energy Buildings, Energy Efficiency, Cost Savings.

I. Introduction

Given the huge energy consumption coming from buildings [2] [3] [4] [5], the development of so-called Net-Zero Energy Buildings (NZEBs) can be crucial for finding a solution at local level. These buildings have an almost optimal energy performance [6] and take their energy mostly from renewable sources, with the objective of balancing annual in- and outcome of energy. Building Integrated Photovoltaics (BIPV) have been studied for helping this process, because of their versatility. In fact, they can be integrated in several ways into the building.

The objective of this paper is to find out which methods have been, and currently are, studied in order to develop the NZEBs idea all over the world, which methods have been tried to increase the energy efficiency and reduce costs.

The paper is structured to have an initial overview on what NZEBs and BIPVs are in detail, continuing with a description of few examples on how these two concepts can work together and which benefits are obtained. Finally, a conclusion will be stated with the main findings.

II. Net-Zero Energy Buildings

Net-Zero Energy Buildings (NZEBs) are defined as buildings with annual net zero energy consumption, or in other words buildings that consume annually the same amount of energy that they produce from renewable sources [7] [8] [9]; for this reason they can be defined as prosumers (both energy producers and consumers).

It is fundamental for these buildings to also have a storage system (electrical or thermal) in order to really be autonomous, to cover peak demand and low renewable sources availability.

The first studies developed on this type of building have been done around 1995, when Gilijamse [10] studied the feasibility of zero energy buildings in the Netherlands. He already stated that PV systems should be the on-site producers for both electricity and heating, it is a feasible system and with a certain heat pump configuration a cost-effectiveness could be reached.

In 2000, the American National Renewable Energy Laboratory (EERE) [11] set a goal of constructing 120,000 NZEBs by 2020.

In 2001, Kadam [12] wrote a review on the available technologies for constructing NZEBs and also analyzed the economical feasibility.

These are just a few examples to see that the concept of NZEBs triggers scientists since more than 20 years. Meanwhile research has progressed and there is the chance of studying them more analytically to find the optimal way to construct them.

However, fluctuations of local demand and variability of renewable on-site energy production systems are too important to be ignored [13]. To reduce this problem, NZEBs need to cooperate in the optimal way with an energy storage system and connection to the electricity grid, so to match the demand load optimizing the energy use: excess energy can be sold and missing energy can be bought from it. However, recent studies are promoting the minimization of the impact on grid by reducing the energy production-demand mismatch [7], thus trying to maximize local energy utilization from renewables and a good management of the load by using smart controls.

III. Building Integrated Photovoltaic systems

A Building Integrated Photovoltaic system (BIPV) is a hybrid Photovoltaic system integrated in the building. PV cells are integrated either in the roof or facade of buildings, usually as an additional layer or as insulating glazing windows [14]. They can be transparent, opaque or colored with any pattern so they can also be pleasant to see. Their functionality is dual: energy generation and replacement of conventional construction elements [15].

Usually a PV needs certain tilt and orientation to optimize its efficiency (defined as the ratio between the possible power generation and the amount of energy received from the sun [15]), but in the case it is integrated in a building this can not be possible. As a solution, the BIPV is installed considering the best orientation that ensures their optimal work, always considering climatic and irradiance conditions of the analyzed area [16], also trying to reduce the shading given by neighbour houses, trees or other objects that would decrease the energy generation potential. In general, when integrating a PV system in a building a compromise between technical and aesthetic requirements has to be found [17]; other integration issues could regard construction materials, construction year or quality of the architecture.

A BIPV has a huge influence on a household's energy demand for heating, cooling and lighting, mainly because they often constitute an extra layer on the building, improving insulation and thus reducing energy consumption [18].

As already mentioned in Section II, energy storage and grid connection are crucial for the supply-demand management. Mainly, they are needed because of the renewable production system, the BIPV: as a matter of fact, the electrical power generated must be consumed immediately, as new power is produced within seconds, and renewable power systems are intermittent, meaning they can not constantly produce energy. Therefore, to avoid wasting electricity already produced and preserve moments where energy can not be produced by the system, excess power can be accumulated in storage systems and, when filled, sent to the grid [19] [20]. This process is necessary to stabilize the household energy availability and guarantee access to electricity during demand peaks.

It is important to understand that NZEBs are expensive and their major costs come from the construction itself, because of the difficulty in implementing several technologies and the materials used, and the combination with BIPVs increases costs even more. For this reason, their diffusion is still very slow.

IV. Examples of studies combining NZEB and BIPV

An overview of NZEBs coupled with a BIPV system will now be presented, either already existing or simulated for researching the optimal manner to combine them, also with other technologies.

A. Coupling a NZEB with BIPV/T

One very interesting example is given by Dumoulin et al. [13] in a paper that studies a building in Montreal (Canada) linking the BIPV/T (BIPV Thermal) system, a specific type of BIPV that includes a thermal component and is coupled with the Heating, Ventilation and Air Conditioning (HVAC) system [21] [22] [23], to an air-source heat pump. It also uses a thermal energy storage (TES) system, so that air can serve as cooling medium for avoiding freezing and reduce maintenance costs. This system is also called BIPV/T-SAHP, where SAHP stands for Solar Assisted Heat Pump, and an example is shown in Figure 1.

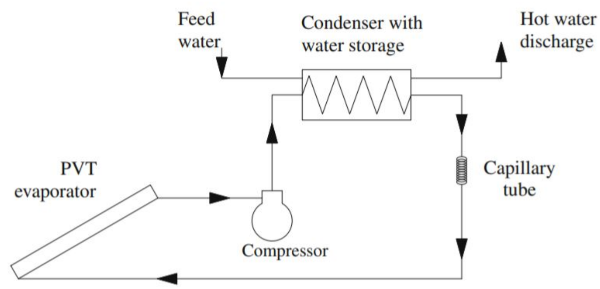

Fig. 1. *Schematic diagram showing the PV/T-SAHP system* [24]

The model created for their simulation is based on 26 alternatives, showing the energy use in terms of electricity consumption, energy efficiency and operation cost during three market phases: buying opportunity, normal operation and selling opportunity. The moment in a day that energy is used is crucial for a household with the scope of optimizing energy use. The following definitions are very important for understanding the main phases of energy production, consumption and interaction with the grid of a similar building.

Buying opportunity corresponds to off-peak periods, when energy use is encouraged through control sequence. Usually it happens during the night, thus there is no contribution from on-site energy production (BIPV/T). During this phase relative energy increases when heat pump and storage size increase.

Normal operation corresponds to mid-peaks, when energy usage is encouraged if enough solar irradiance is available, so to take advantage of the on-site production energy.

Finally, *selling opportunity* corresponds to peak periods, when energy use is discouraged in favor of using stored heat for the heating demand.

There are two other factors that are mentioned that are very important. *Supply cover* factor indicates how much on-site generated electricity is consumed locally. On-site production happens mostly during late morning or early afternoon (period corresponding to normal operation during hot seasons). In this period solar irradiance is usually higher and for this reason a high supply factor is encouraged, while there are no incentives to sell to the grid. When the TES size is smaller, self-consumption is lower because the minimum desired storage is quickly reached. On the contrary, during the selling period, is encouraged to sell electricity to the grid for reducing peak power demand, and consequently self-consumption has to be avoided. Systems with large TES and HP size have the lowest supply cover factor during selling period. When implementing the entire BIPV/T system, the overall system performance increased, thanks to the utilization of heat storage together with more effective heat generation in the system.

The second factor is *demand cover*, the amount of energy demand covered by local power generation in a time period. Normal operation is always when sun is most available and in this way 80% of energy demand is covered by local energy. Selling period starts in early morning, thus all energy consumed in that moment does not come from on-site production.

This paper results show that the TES capacity is more important than the HP size, which is logical since the main objective is to make the household system flexible in handling energy production and use. As for energy efficiency, a larger TES leads to higher gains (an average heat pump COP increases by 22% when a BIPV/T system is added. During peak sun conditions, it can increase by 50%). Operational costs savings can be up to 40% and promote energy usage when is optimal for the grid. Savings in general increase with increasing TES size and implementing BIPV/T.

These two results show the importance of integrating such a system in households.

B. BIPV/T system and ventilate concrete slab in Canada

Climate in Canada tends to be cold but relatively sunny, reason why this paper by Chen et al. [25] focuses on designing a NZEB based on an air-based open loop BIPV/T for electricity and heat production, with a ventilated concrete slab (VCS), used in floor and walls for the partial absorption of solar radiation, to overcome the usual low ambient temperatures.

The combination of these two components, a solar technology and a highly insulated building, needs further studies to be optimized for cost reduction that will help NZEBs being widely adopted in the future. For the moment, results are promising since energy consumption can come entirely from on-site production and the help of insulation increases energy efficiency.

C. Energy efficiency variation with a different amount of BIPV glazing panels

The simulation described in the paper from Domjan et al. [14] analyzes the energy efficiency indicators variation in buildings whose facades are covered with different layers of BIPV in the form of glazing panels. Glazing panels (and also semi-transparent panels) have a higher electrical efficiency compared to opaque PVs [26]. The panels used are considered to be the best available technology thanks of their complete solar energy transmittance and low thermal transmittance, which gives the building a nice ambient temperature, and also a good daylight transmittance.

In this particular case study the PV cells are installed with a chessboard layout in the BIPV glass structure in order to have a PV area not bigger than 60% of the facade.

Four scenarios are considered and compared to a reference Double Glass curtain wall, *glazing with 4 panels*, *glazing with 6 panels*, *glazing with 7 panels* and *glazing with 6 panels and thermal insulation core*. Each building can either have a biomass district for heating and cooling, a heat pump for heating and cooling or gas for heating. The specifics of these plants can be seen in Table 2 of the paper [14]. The simulation has been done in different cities (Helsinki, Zurich, Barcelona) to test the changes that depend on the geographical area.

In Helsinki, when buildings use a biomass district for heating and cooling, there would be a decrease in the final energy demand of almost 50% if a six-panel glazed facade is used, compared to the reference Double Glass.

In Zurich, using a heat pump for both heating and cooling, advanced facade structures reduce significantly the non-renewable primary energy needed, but there is no significant decrease of final energy demand.

In Barcelona, using a gas boiler for heating and a heat pump only for cooling, in an all glass building the internal gains have a huge impact on the size of the BIPV, which has to be installed northwards.

In conclusion, this paper demonstrated through a simulation that all the studied buildings can meet the NZEB requirements if using advanced glazing and producing on-site energy with the BIPV.

D. Transformation of a building into a NZEB

A university in Spain has performed an analysis on the transformation of a building into a NZEB [27], implementing BIPVs in the facade. The main environmental impact comes from the manufacturing phase of PVs, but with over 30 years of lifetime the system would avoid much more emissions, leading to an impact reduction of 53%.

E. NZEB design in the UK

A case study by Wang et al. [28] shows using computer simulations how to design an optimal NZEB and avoid large costs due to construction experiments. After analyzing the local climate data, they identified the most important methods to minimize the energy load requirements: energy efficient heating is reached through a domestic hot water system (DHW) coming from a BIPV, using an underfloor heating system for the entire household. Furthermore, the electric system is also powered by the BIPV and is indispensable for this type of building.

This study is from 2009, thus a bit dated, but its conclusion already states that it is possible to achieve NZEBs in the UK, since the annual electricity production is predicted to cover the electricity need for all appliances.

F. NZEB simulation in Montreal in early 2000s

Biaou et al. [29] in 2006 performed a simulation of a NZEB in Montreal, Canada. Such a simulation in the early 2000s is quite interesting, considering that at that time this system was even more idealistic that it is now and the software was quite simple.

The simulated household is equipped with a BIPV, which at the time did not have the Building Integrated concept yet so was simply called a PV, and a geothermal heat pump for heating and cooling. Water is pre-heated and on-site electricity production is used for appliances.

The results found by the analysis are promising: the system during winter would get from the grid more electricity than the amount produced on-site by the PV, but during summer the opposite occurs and overall a net zero energy balance is reached at the end of the year.

V. Conclusion

Several examples have showed how integrating BIPVs into buildings is a solution for developing optimal NZEBs. The major benefits regard an increase in both energy efficiency and energy-related cost savings, and the improvement in demand-supply match given by the connection to the electricity grid and the presence of an energy storage. Even though benefits are very interesting, this type of buildings are expensive and this restrains their construction. There is then an important trade-off between high initial costs and elevated operational cost savings. In any case, realistically, developing only NZEBs would be an utopia for many reasons, but being able to develop nearly-NZEBs would still be a huge achievement.

We are still far from constructing loads of NZEBs and mitigating the majority of energy consumption problems derived from the built environment, however the cited examples show that it is possible to find innovative solutions. Some research is still needed for this topic and the next step would be to already implement more and more NZEBs all over the world, especially in developing countries, where many buildings will be constructed in the near future, which is simpler than modifying existing buildings to meet the requirements.

References

[1] D. Crawley, S. Pless, and P. Torcellini, "Getting to net zero," National Renewable Energy Lab.(NREL), Golden, CO (United States), Tech. Rep., 2009.

[2] L. Pérez-Lombard, J. Ortiz, and C. Pout, "A review on buildings energy consumption information," *Energy and buildings*, vol. 40, no. 3, pp. 394–398, 2008.

[3] M. Santamouris, N. Papanikolaou, I. Livada, I. Koronakis, C. Georgakis, A. Argiriou, and D. Assimakopoulos, "On the impact of urban climate on the energy consumption of buildings," *Solar energy*, vol. 70, no. 3, pp. 201–216, 2001.

[4] X. Li, C. P. Bowers, and T. Schnier, "Classification of energy consumption in buildings with outlier detection," *IEEE Transactions on Industrial Electronics*, vol. 57, no. 11, pp. 3639–3644, 2009.

[5] D. D'Agostino, B. Cuniberti, and P. Bertoldi, "Energy consumption and efficiency technology measures in european non-residential buildings," *Energy and Buildings*, vol. 153, pp. 72–86, 2017.

[6] S. Attia, "Chapter 1 - introduction to nzeb and market accelerators," in *Net Zero Energy Buildings (NZEB)*, S. Attia, Ed. Butterworth-Heinemann, 2018, pp. 1–20. [Online]. Available: https://www.sciencedirect.com/science/article/pii/B9780128124611000010

[7] U. Berardi, *ZEB and nZEB (definitions, design methodologies, good practices, and case studies)*, 05 2018.

[8] B. M. Ahmed and N. F. F. ALhialy, "Optimum efficiency of pv panel using genetic algorithms to touch proximate zero energy house (nzeh)," *Civil Engineering Journal*, vol. 5, no. 8, pp. 1832–1840, 2019.

[9] J. Kurnitski, F. Allard, D. Braham, G. Goeders, P. Heiselberg, L. Jagemar, R. Kosonen, J. Lebrun, L. Mazzarella, J. Railio *et al.*, "How to define nearly net zero energy buildings nzeb," *Rehva Journal*, vol. 48, no. 3, pp. 6–12, 2011.

[10] W. Gilijamse *et al.*, "Zero-energy houses in the netherlands," in *Proceedings of building simulation*, vol. 95, 1995, pp. 276–83.

[11] N. R. E. L. (EERE), "Zero net energy buildings, outreach and action plan." 2000.

[12] S. Kadam, "Zero net energy buildings: are they economically feasible," *Sustainable Energy Proceedings. Spring*, 2001.

[13] R. Dumoulin, E. D. Rounis, and A. Athienitis, "Operation and grid interaction modeling of a house with a building integrated photovoltaic thermal (bipv/t) system coupled to an air-source heat pump," *Science and Technology for the Built Environment*, pp. 1–19, 2021.

[14] S. Domjan, S. Medved, B. Černe, and C. Arkar, "Fast modelling of nzeb metrics of office buildings built with advanced glass and bipv facade structures," *Energies*, vol. 12, no. 16, p. 3194, 2019.

[15] I. Cerón, E. Caamaño-Martín, and F. J. Neila, "'state-of-the-art'of building integrated photovoltaic products," *Renewable Energy*, vol. 58, pp. 127–133, 2013.

[16] A. Boccalatte, M. Fossa, and C. Ménézo, "Best arrangement of bipv surfaces for future nzeb districts while considering urban heat island effects and the reduction of reflected radiation from solar façades," *Renewable Energy*, vol. 160, pp. 686–697, 2020.

[17] F. Frontini, M. Manfren, and L. C. Tagliabue, "A case study of solar technologies adoption: criteria for bipv integration in sensitive built environment," *Energy Procedia*, vol. 30, pp. 1006–1015, 2012.

[18] A. Dobrzycki, D. Kurz, S. Mikulski, and G. Wodnicki, "Analysis of the impact of building integrated photovoltaics (bipv) on reducing the demand for electricity and heat in buildings located in poland," *Energies*, vol. 13, no. 10, p. 2549, 2020.

[19] M. A. Eltawil and Z. Zhao, "Grid-connected photovoltaic power systems: Technical and potential problems—a review," *Renewable and sustainable energy reviews*, vol. 14, no. 1, pp. 112–129, 2010.

[20] H. Zsiborács, G. Pintér, A. Vincze, Z. Birkner, and N. H. Baranyai, "Grid balancing challenges illustrated by two european examples: Interactions of electric grids, photovoltaic power generation, energy storage and power generation forecasting," *Energy Reports*, vol. 7, pp. 3805–3818, 2021.

[21] M. Trčka and J. L. Hensen, "Overview of hvac system simulation," *Automation in Construction*, vol. 19, no. 2, pp. 93–99, 2010.

[22] A. Pugsley, A. Zacharopoulos, J. D. Mondol, and M. Smyth, "Bipv/t facades–a new opportunity for integrated collector-storage solar water heaters? part 2: Physical realisation and laboratory testing," *Solar Energy*, vol. 206, pp. 751–769, 2020.

[23] S. M. Sultan and M. E. Efzan, "Review on recent photovoltaic/thermal (pv/t) technology advances and applications," *Solar Energy*, vol. 173, pp. 939–954, 2018.

[24] T. T. Chow, K. Fong, G. Pei, J. Ji, and M. He, "Potential use of photovoltaic-integrated solar heat pump system in hong kong," *Applied Thermal Engineering*, vol. 30, no. 8-9, pp. 1066–1072, 2010.

[25] Y. Chen, A. Athienitis, and K. Galal, "Modeling, design and thermal performance of a bipv/t system thermally coupled with a ventilated concrete slab in a low energy solar house: Part 1, bipv/t system and house energy concept," *Solar Energy*, vol. 84, no. 11, pp. 1892–1907, 2010.

[26] D. Kamthania, S. Nayak, and G. Tiwari, "Performance evaluation of a hybrid photovoltaic thermal double pass facade for space heating," *Energy and Buildings*, vol. 43, no. 9, pp. 2274–2281, 2011.

[27] G. Y. Palacios-Jaimes, P. Martín-Ramos, F. J. Rey-Martínez, and I. A. Fernández-Coppel, "Transformation of a university lecture hall in valladolid (spain) into a nzeb: Lca of a bipv system integrated in its façade," *International Journal of Photoenergy*, vol. 2017, 2017.

[28] L. Wang, J. Gwilliam, and P. Jones, "Case study of zero energy house design in uk," *Energy and buildings*, vol. 41, no. 11, pp. 1215–1222, 2009.

[29] M. Bernier, Y. Ferron, and A. Biaou, "Simulation of zero net energy homes," *Journée thématique du*, vol. 21, 2006.