TITLE

The Zero Building: an exemplary nearly zero energy office building (NZEB) and its potential to become a positive energy building (PEB).

AUTHORS

X. Barrutieta [a,b,*], Gainza J. [a], O. Irulegi [a], R. Hernández [a]

[a]CAVIAR – Quality of Life in Architecture Research Group, Architecture Department, University of the Basque Country UPV/EHU, Plaza Oñate 2, 20018 Donostia-San Sebastián (Spain)
[b]Barru Arkitektura SLP, Carlos I 28, 20011 Donostia-San Sebastián (Spain)
*Email address: xabier.barrutieta@ehu.eus (X. Barrutieta)
URL: https://www.barruarkitektura.com (X. Barrutieta)
ORCID: ResearcherID: P-9258-2016

WORD COUNT

6720

ABSTRACT

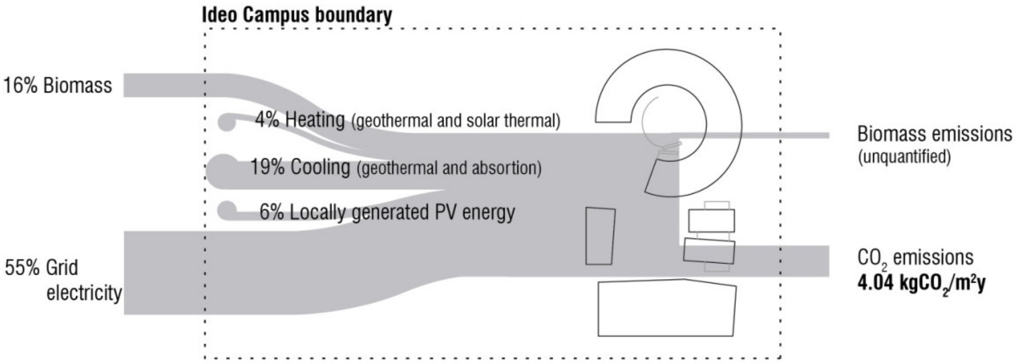
European energy policies introduced nearly zero energy building (NZEB) design to stimulate the energy transition in buildings, and EU programs promote the evolution towards positive energy buildings (PEB). Most studies into NZEBs are based on **simulations**, and not on **real monitoring data.**

This paper presents the real performance data of the Zero building, an NZEB office building with Leed Gold and Breeam Excellent environmental design certifications located in a neighbourhood that shares a zero-emission district heating-cooling facility relying only on **100% renewable energy sources.**

The current performance of the building and its neighbourhood is assessed to identify the existing gap to reach the goals of next generation buildings, namely positive energy buildings (PEB), which will not consume fossil fuels and will achieve energy self-sufficiency at the neighbourhood scale.

A study the occupied zero building in operation for one year showed that it achieved a degree of **self-sufficiency** of **74.3%** for the **operational electric energy** thanks to its PV roof-façade. The results show that its carbon footprint is only **3.35** $\mathbf{kgCO_2/m^2y}$, **92%** lower than in a typical office building in locations with the same climate.

GRAPHICAL ABSTRACT



Graphical Abstract. Energy analysis at the Ideo Campus boundary, and corresponding CO_2 *emissions.*

KEYWORDS

Low carbon building
Energy and environmental design
Office building
Case study
Building monitoring
Zero emission neighbourhoods
Zero building
Net zero energy building (NZEB)
Positive energy building (PEB)

1. Background

In recent years the concept of nearly zero energy buildings (NZEB) has received widespread international attention. In Europe, the Energy Performance in Buildings Directive (EPBD) 2010/EU/31 (European Parliament, 2010) defined the nearly zero energy building (NZEB) concept in general terms as a new type of low energy building that would result in the construction sector consuming less energy and a drastic reduction in emissions of greenhouse gases (Torcellini et al., 2006). Many different definitions were applied at that time (BPIE, 2010) and extensive research was performed to find a common definition. (Igor Sartori et al., 2012). Some broadly accepted definitions are (Pless & Torcellini, 2010): **net zero energy buildings** refer to buildings that can create all the energy they consume over a given period. It can also be the case that the building produces more energy than it consumes, making it a positive energy building. **Net zero emission buildings** prioritize the non-emission of greenhouse gases by burning fossils in the plot itself. **Nearly zero energy buildings** are defined through more qualitative criteria. First, they have a very low energy demand; second, the greater possible demand of the building is met with renewable energies; and third, they produce this energy as close to the building as possible.

By the end of 2020 all new buildings in the European Union have to comply with the NZEB standard as defined by each country member. In 2018, a new version of the EPBD UE2018/844 was released consistent with the Energy and Climate Policy Framework for 2030, which aims to reduce greenhouse gas emissions by at least a further 40% by 2030 compared with 1990. To meet this goal, EU programs promote the NZEB design and its evolution, namely the positive energy building (PEB) model, which represents an improvement on NZEB and consists of buildings that produce more energy than they consume. The strategies to achieve PEBs are under discussion (Cole & Fedoruk, 2015), but they will likely be based on the NZEB buildings that are currently in use. The 2010s can be identified as the first generation of NZEBs and it is time to assess the real performance of example buildings in order to respond to future challenges by 2030.

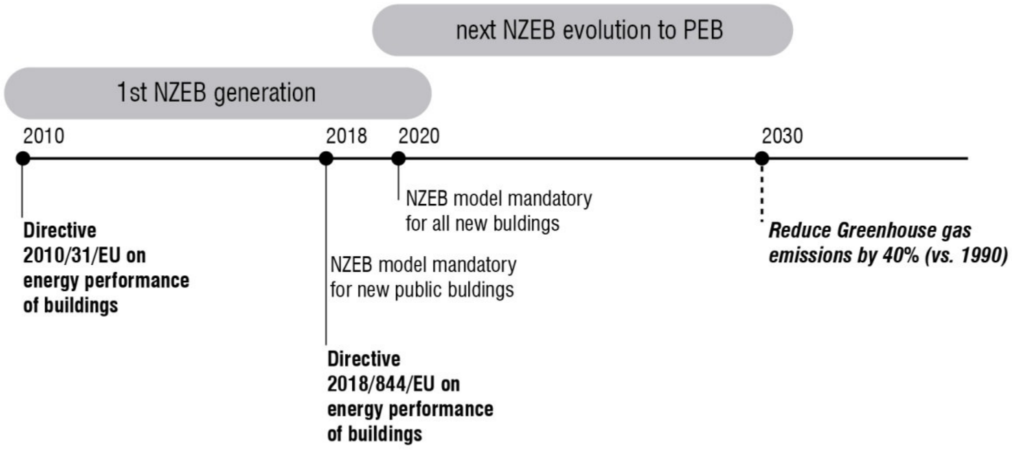


Figure 1. European NZEB model introduction and the challenge of its evolution towards PEB.

1.1. The next challenge: from nearly zero energy buildings (NZEB) to positive energy buildings (PEB).

Numerous building projects have been presented as having net-zero energy performance, but such claims involve the use of a variety of approaches. The problem to overcome is that there is a lack of studies that discuss the real energy performance of these first generation NZEBs. These data would enable them to be compared and provide information from previous projects to confront the design of the evolution towards PEBs.

This situation explains the aim of the paper:

Through a case study, with real energy consumption data, an exemplary NZEB office building is studied to unveil its potential to become a next generation positive energy building.

The objectives are to:

- Identify the design strategies that improve its energy efficiency.
- Analyse the shape and envelope of the building regarding the incident solar radiation, its solar capture potential and the internal building spaces.
- Analyse the renewable energy mix to avoid fossil fuels at district scale and the contribution to the operational and total energy consumption.
- Identify the performance gap between simulation and real performance data, and its possible reasons.
- Measure the degree of energy self-sufficiency achieved by the Zero building to serve as a reference for similar building designs in the future.
- Perform a sensitivity analysis of possible actions to turn the building ensemble into a zero CO2 emission neighbourhood.

1.2. Building monitoring.

There are several publications on low carbon and NZEB office buildings that refer to energy performance data. Most of these studies are based on theory and simulations, not on monitoring data from real buildings. In this context, there is a lack of studies of the operational phase of these buildings that aim to show the degree of satisfaction of the design solutions adopted and their effectiveness (Lenoir et al., 2012). A study that analysed two similar office buildings based on the recognitions of excellence in sustainable architecture and green construction in their countries revealed over sevenfold differences between buildings regarding the end-use energy and over 40-fold differences if the primary energy is calculated (Attia, 2016).

Researchers have highlighted the difficulty of comparing NZEB buildings of any kind worldwide despite considering a broad selection of buildings (Hyde et al., 2012). This is mainly due to inconsistent zero carbon concepts and methodologies that hamper benchmarking (Kurnitski et al., 2013) (Pan & Li, 2016). One of the most extensive studies into net zero energy buildings worldwide (Musall et al., 2016) comprised 280 NZEBs with the aim to show trends, the intentions of the principal stakeholders and the methods followed to achieve a zero energy balance. Some authors argue that there are very few reported examples of low-energy offices (Flodberg et al., 2012); one study based on simulations focuses only on zero-carbon design in offices (Jones et al., 2015). Some of the few studies reporting real data are the case-study of a green office building in China (Zhou et al., 2016) and a net zero energy office building in Berlin (Ascione et al., 2016). The former showed that energy consumption was much higher than the energy generated by the solar PV system due to differences in the equipment between operation and design stages, the user behaviour pattern and less energy being generated by the PV panels. The net-zero office building in Berlin showed almost threefold differences between the expected and measured electricity usage for heating and DHW, but also a higher yield of the PV system.

1.3. Importance of climate responsive design

In nearly zero energy buildings the energy demand is closely linked to its geographical and climate situation. Several studies propose specific roadmaps for different climates and countries (Deng et al., 2014), as even in the same country several climates may co-exist and the strategies for NZEB design vary significantly. In some cases, heating and/or cooling load predominance has been taken as a classification criteria (Garde & Donn, 2014). The Solar Decathlon competition has also served as a test bed to study experimental sustainable buildings in diverse climates (Irulegi et al., 2014) (Peng et al., 2015).

A study into climates in NZEBs (Harkouss et al., 2018) focuses on the importance of treating each climate separately and proposes the classification of 30 case studies performed in the 8 major climate zones. Some studies have focused on net-zero building design in hot and humid climates (Sudhakar et al., 2019) and there is evidence of experiences learned from 34 case study buildings for these climates (Feng et al., 2019). Concerning office buildings, one study simulated their performance in three different climates (Jung et al., 2018). References to oceanic or mild climate NZEB design and case study analyses are less common. Research into the specificities of climate constraints that discusses the strategies for confronting several challenges that NZEBs face takes the temperate oceanic climate as a reference (Moran et al., 2017). A study aiming to apply a normalization method to compare the energy performance of office buildings simulated a reference building corresponding to Japanese ZEB Ready performance moving to European Oceanic and Nordic climates (Ahmed et al., 2019).

1.4. From the Building to the Neighbourhood.

Low carbon buildings have higher possibilities of success in low carbon neighbourhoods. From an architectural and urban planning perspective, there are several interesting aspects when applying the low carbon principle to the intermediate urban scale (Amaral et al., 2018). The complexity embraced at this scale makes it possible, among other things, to materialize a self-sufficient integrated design approach in terms of goods, services and energy (Barrutieta, 2010). From an energy perspective, this approach presents unique opportunities to cost-effectively achieve high levels of energy efficiency and renewable energy penetration across a collection of buildings, which may be unfeasible at the individual building scale (Polly et al., 2016), and even reach the goal of an energy positive neighbourhood (Ala-Juusela et al., 2016).

There is a need to assess buildings and neighbourhoods homogeneously in order to learn more about how they operate (Newton & Tucker, 2010). This will be key to designing increasingly sustainable and energy efficient buildings and cities. With this objective in mind, the Zero-Plus project (*ZERO-PLUS*) of the European research and innovation programme, Horizon 2020, examined the benefits and barriers associated with the implementation of the net zero energy (NZE) concept at a settlement scale. Four case studies revealed that the initial cost of developing NZE settlements is on average 16% lower than the cost of a typical NZEB, but the study also raised the issues of the regulation barriers and the challenge of managing and integrating all the needs of the stakeholders (A. Mavrigiannaki et al., 2021). Measurement and verification of the performance against expected targets was implemented as an integral part of the project management and development process, which, apart from allowing for the evaluation of the adopted energy efficiency measures, benefits multiple aspects related to the design and operation of buildings (Angeliki Mavrigiannaki et al., 2020). Other European Horizon 2020 projects are working on demonstrating that near zero energy buildings can be transformed into positive energy buildings (EXCESS) and on creating positive energy districts (ATELIER).

1.5. Methodology

Real measurement data of the Zero building and its neighbourhood are presented and discussed in this paper. The aim is to obtain applied and real knowledge about the project decisions adopted so that the conclusions will serve as a guideline for similar or evolved solutions in future projects where the type of building and climate conditions are similar.

This case study represents a unique case because it is a non-residential building with singular architecture and a bioclimatic design approach that obtained Leed Gold and Breeam Excellent environmental design certifications. It is part of a neighbourhood with no local fossil fuel consumption. The case study is presented by the authors of the architectural design and construction management of the Zero building and its neighbourhood.

After the commissioning of the building, energy data was monitored in both the building and the district heating/cooling (DHC) facility for a one-year period from summer 2014 to summer 2015. The measured energy corresponds to the real end-use energy that is not affected by country or region-specific primary energy weighing factors.

The thermal energy was measured by 83 energy meters distributed in the radiant floor heating cabinets and the HVAC systems of the buildings. Energy production was also measured at the DHC facility to control the energy losses of the distribution ring, these losses being shared proportionally to the acclimatized area of each building. All building data are integrated and managed by a common supervisory control and data acquisition (SCADA) system for the whole campus.

For the electricity measurements, there were 45 energy meters in the Zero Building and 35 more for the Ideo Campus connected with M-Bus modules. These devices allow the measuring of the consumed operational energy and household electricity on each of the floors of the buildings.

As there is no carbon emission source on the site, CO_2 emissions of the non-renewable energy part of the consumed grid electricity were calculated using the data provided by the electricity supplier for the monitored period.

The study aims to gain real knowledge that can be applied to future project designs to meet the challenge of designing positive energy buildings and districts.

Therefore, the degree of energy self-sufficiency and the corresponding carbon footprint at the scale of the Zero building and the neighbourhood scale will be calculated.

The simulation program used is LIDER-CALENER, the official software used for regulation purposes in Spain (IDAE, 2021). LIDER-CALENER uses a dynamic and multi-zone detailed simulation model to perform simulation in free-floating mode and calculations of the heating and cooling requirements of buildings. In this simulation, the typical office building is presented as the reference building. The CO_2 emissions from the Zero building amount to 14.2 $kgCO_2/m^2y$, which is 37% of the emission of the reference building and results in it achieving an A rating.

The results related to the consumed energy will make a distinction between the operational energy and the total energy of the building. The operational energy corresponds to the technical building systems as stated in the EPBD for office buildings, which include energy consumed for heating, cooling, hot water systems, lighting and ventilation; it excludes energy used for other appliances such as elevators, computers, machines, communication gadgets, etc., commonly referred to as plug loads. The total energy is the sum of all these loads.

2. The Zero Building Case Study

This is an example of a building developed when the NZEB model was not widespread, and largely before the evolution towards PEB. It helps to testify the maturity of the technologies applied and the aspects of its design that have impacted its success with regard to energy efficiency.

The Zero building is located in Hernani, close to San Sebastian (Basque Country) on the Northern Atlantic coast of Spain, at a latitude of 43.2765 and longitude −1.9871 and is 30 m above sea level. The site receives 1265 mm of rain per year. The August high is around 25 ºC on average and January low is 6 ºC. It has an oceanic climate considered Cfb according to the Köppen-Geiger classification (also known as marine west coast climate) (Wikipedia (a), 2014). This climate applies in several locations worldwide, from the Australian south-east coast to the Atlantic coast in European countries.

The Zero building is part of the Ideo Campus in the neighbourhood that embraces the joint design of four buildings (Zero, Foundation, Gallery and A3 building), infrastructures and urban spaces.

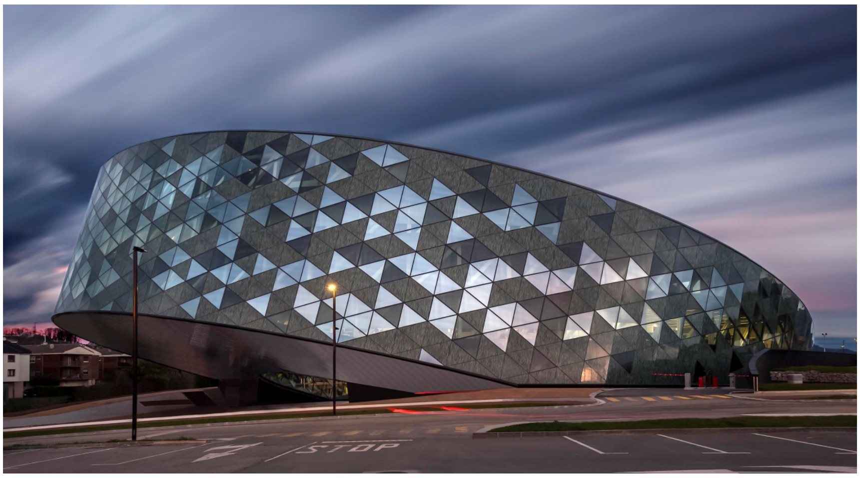


Figure 2. Front façade of the Zero building.

Figure 3. Inclined PV roof of the Zero building.

2.

2.1. Energy and environmental design

The Zero building houses offices in around 17,500 m^2. Its shape is a hollow cylinder 90m in diameter and 16 meters high, inclined 15ºs on the horizontal plane. The roof slopes southwards to take advantage of the position of the sun and maximize the solar gain of the PV roof. The workspaces are located near the outer exterior facade of the building in a circular 11m bay, which mainly faces north to allow a generous entrance of natural light to the office areas while minimizing overheating by solar radiation. The inner south-facing ring-shaped gallery distributes the flow of people and acts as a greenhouse that permits passive heat gain. Between these two rings are the stairs, lifts, toilets, utility shafts, etc.

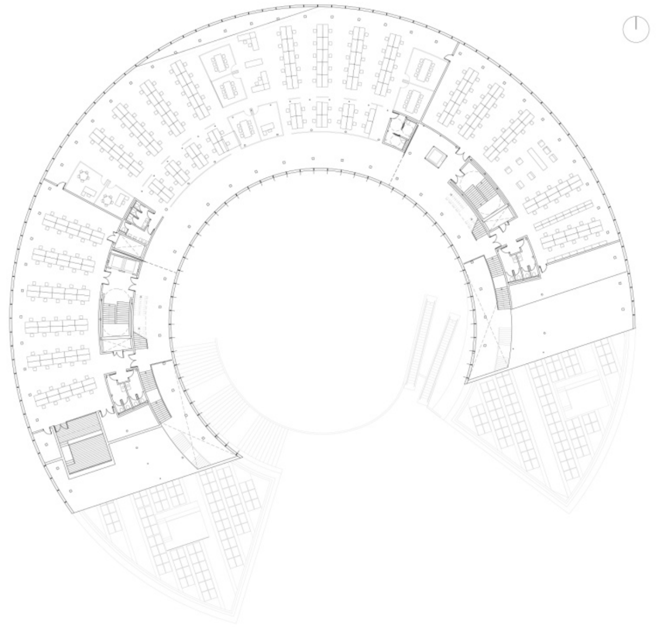


Figure 4. Floor plan of the first floor of the Zero building.

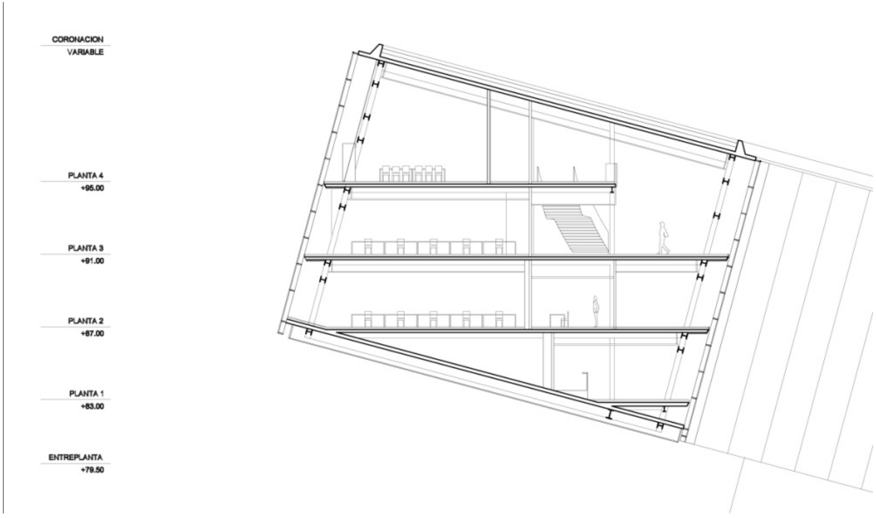


Figure 5. Building section from the symmetry axis of the Zero building.

Parametric façade design

The curved facade is composed of triangular pixels that characterize the image of the building. These pixels are opaque, translucent or transparent depending on their position and the different circumstances regarding exposure to solar radiation, access to views, the relation with the use of internal space, etc. Solutions for the outer and inner façades are designed with the aid of the superposition of these variations on the façade development and taking into account the overall transmittance and a reference threshold for heat loss, each with a different ratio of openings and opaque areas. Overall, there are approximately 40% transparent triangles, 40% opaque and 20% translucent, which reaches a U-value of 1.2 W/m^{2}K.

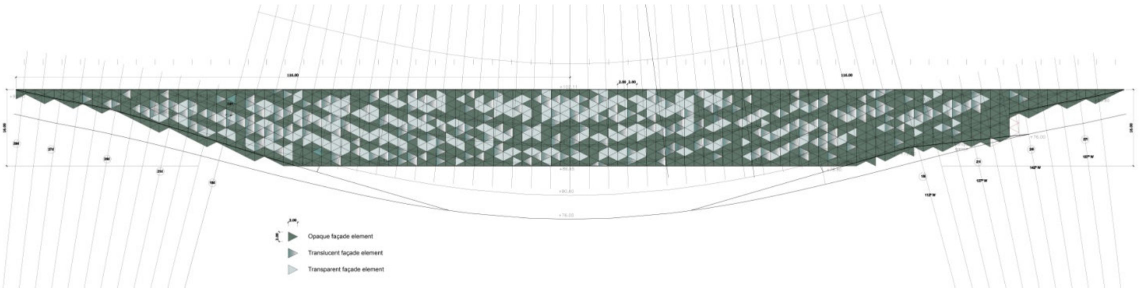


Figure 6. Triangulated curtain wall composed of opaque, translucent, and transparent elements represented on the unfolded cylindrical façade of the Zero building. The design responds both to the incident solar radiation and use of the interior space in the building.

The natural light, the views, the acoustic comfort, the connection with nature and vegetation were some of the aspects taken into consideration when designing the façade. Consequently, the building was selected by the World Green Building Council as a benchmark for health, wellbeing and productivity in offices (World Green Building Council, 2015).

Figure 7. Inner view of the south facing circulation gallery where different elements of the curtain wall can be observed.

2.2. Energy generation

The zero building was designed to achieve the ambitious goal of being 100% fossil free and a zero-emission building. The design concept to reach this objective rests on three basic pillars: building design with a low energy demand; 100% renewable energy consumption; and the local generation of the renewable energy. The project is compliant with these goals and therefore can be considered a benchmark for the standard to be implemented throughout the whole of Europe from the year 2021 and beyond.

The energy use in the building is based on the premise of making the most of the district heating-cooling system on the whole, which is powered totally with renewable energy sources: biomass, thermal solar and geothermal. The water that is heated or cooled using the district heating-cooling system is distributed to the substations located in each of the buildings. The sizing of renewable systems has been done with the aim of maximising the number of hours in which these energies are effective, giving priority to the geothermal, then the solar thermal and finally the biomass. These are the installed renewable energy systems and powers:

Heating:
- Biomass boilers 2x 600 kW
- Geothermal heat pump: 194 kW
- Solar thermal installation: 90 kW

Cooling:
- Geothermal cool pump: 154 kW
- Absorption machine: 176 kW
- Chiller

This thermal power station centralizes the production of hot and cold water that is allotted to each of the buildings at the Ideo Campus by means of a closed distribution ring at “medium temperature” (45-55 ºC), and thus it is suitable for both the radiant floor heating and cooling, and fan coils. Figure 8 shows the energy flows for the whole campus:

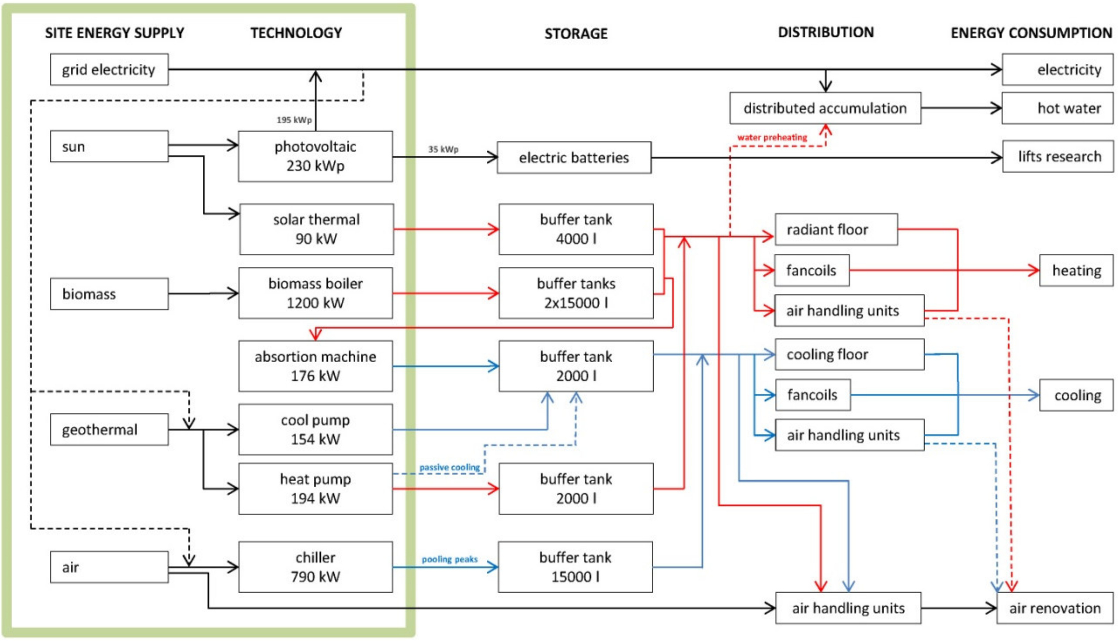


Figure 8. Energy generation, technologies, storage, distribution and consumption for the Ideo Campus.

Regarding the production of electricity onsite, the strategy has been to specialize the zero building as a solar energy collector for the whole campus. The inclined roof is covered by strips of photovoltaic panels with an optimum orientation.

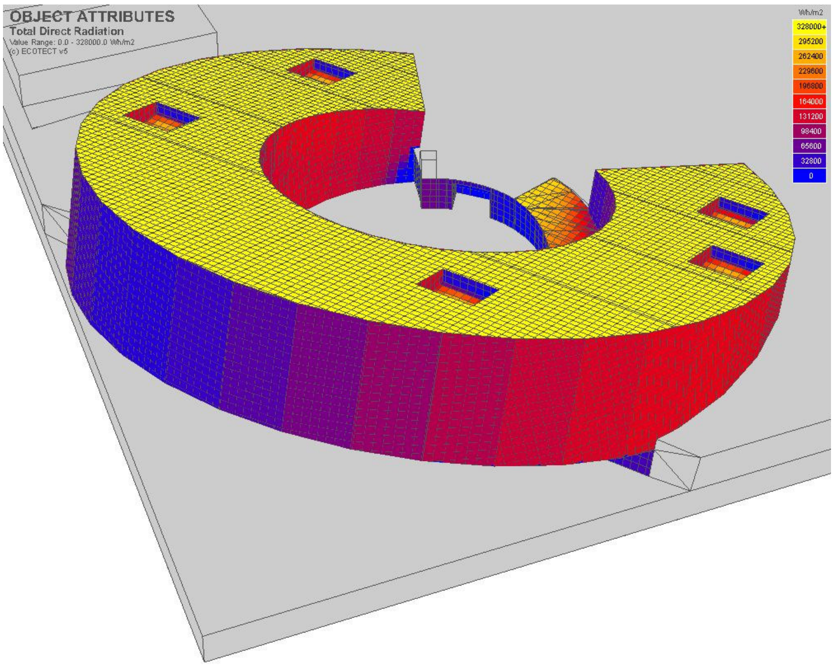


Figure 9. Simulation of accumulated direct solar radiation for the Zero building during the summer months. The colour bar scale shows a gradient for Wh/m^2 units.

The geothermal energy wells are located under the common parking floor of the campus, and the solar thermal collectors are situated on the roof of the Foundation building.

The following chart presents the different buildings of the Ideo Campus with their basic parameters.

Ideo Campus Buildings	Dominant use	Floor area m^2 above ground
ZERO	Office and corporative	17,505.62
FOUNDATION	Educational	7,924.37
A3	Research	1,723.31
GALLERY	Research	758.12

Table 1. Buildings at the Ideo Campus and their floor area.

2.3. Thermal comfort management

The comfort temperature is set to 20 ºC during the winter period and 24 ºC during the summer both for the simulations made during the project phase and for the monitored period. The occupants are given the option to modify this temperature locally in each of the areas by a range of ±2 ºC. The displays do not show the actual measured temperature to avoid biased behaviours from the occupants. Windows are incorporated in the triangulated curtain wall façade to permit their opening for ventilation by the users, and the centralized Building Management System (BMS) controls that they are properly closed when needed.

3. Results and Discussion

3.1. Zero building energy monitoring data.

The overall surface area of the Zero building is 17,505m^2 above ground and 7,029m^2 underground. For the energy calculation, only the heated and cooled surface of the building has been considered.

End-use energy and primary energy

The measured energy in the Zero building and the Ideo Campus corresponds to the real end-use energy (or final energy) consumption in the building during a whole year of operation. This energy can be transformed into primary energy figures by the application of weighting factors which vary in different countries (I. Sartori & Hestnes, 2007). The Building Performance Institute Europe (BPIE) argues that the current approach, using primary energy factors (PEFs) is detrimental to understanding the real energy performance of a building (BPIE, 2017). Therefore, end-use energy has been taken as a reference for this case study, as it is a direct comparable real measurement unit that reflects the building energy performance and facilitates the possible later comparison to other similar case studies (Jung et al., 2018).

Thermal energy consumption

The systems designed for the thermal energy transfer integrated in the Zero building are mainly under floor heating and cooling for the office and circulations areas, and ducted fan-coils for certain areas such as auditoriums and some meeting rooms. The thermal energy consumption for the Zero building in the monitored period was 35.74 kWh/m^{2}y for heating and 39.91 kWh/m^{2}y for cooling.

A whole year operation of the occupied building has been compared to the simulations run during the project phase. These simulations were made with the LIDER-CALENER simulation software and predicted a demand of 123.8 kWh/m^{2}yfor heating and 22.3 kWh/m2 for cooling. This shows that the real performance of the building has resulted in a significantly lower demand for heating (-71%) and a higher energy need for cooling the building (+79%).

This could be due to some singular aspects of the building that will require further analysis:
- The difficulty to predict the passive solar behaviour of the southern facade acting as a greenhouse, thus resulting in more passive heat gain.
- Higher cooling energy needs to fulfil the comfort demands, as the 24 ºC summer indoor temperature set to reduce the energy consumption was not broadly accepted by the occupants. No specific dress code is needed in the building.

Electrical energy consumption

The annual operational energy of the Zero building necessary to meet the liveability conditions for its occupants is **368.049 kWh.** This figure can be divided into the following systems:

Zero building - Total electricity of "technical building systems" kWh/y	**368,049**	100.0%	**21.02**	kWh/m2a
Heating-Cooling DH	138,087	37.5%		
Ventilation	35,897	9.8%		
Domestic Hot Water DHW	12,372	3.4%		
Lighting	165,778	45.0%		
Humidity control	15,914	4.3%		

Table 2. Electrical energy consumption of the building technical systems for liveability conditions at the Zero building distributed by systems according to 2010/31/EU Directive.

The rest of the energy consumption in the building is also relevant as it includes the computers, data centre, laboratories, lifts, etc. The annual energy consumption of the rest of the energy uses for the Zero building amounts to **828,507 kWh.** This amount should be considered in the global scope of the building design, as this energy also needs to be available for the building to be fully operative.

In conclusion, the operational electrical energy necessary for the technical building systems of the Zero building represents **30.75%** of its yearly total electricity consumption.

Photovoltaic Solar Energy Production

Renewable electrical energy is produced through the integrated solar panels on the inclined roof of the Zero building. All the polycrystalline photovoltaic panels are placed on the roof at a 15 degree angle from the horizontal, which enables them to perform at over 95%. The total installed peak power is **230 kWp**, and the monitored amount of energy produced annually is **273.380 kWh.**

The integrated design approach at a neighbourhood scale is important at this point, as the strategy is for the Zero building to generate solar energy for all the buildings on the campus. Therefore 41% of the produced electricity is consumed by Zero and the remaining **59%** of the solar panels installed on its roof generate energy for the other surrounding buildings, namely, the Foundation, the A3 research and Gallery buildings.

CO_2 emissions

A reduction in CO_2 emissions for the built environment, along with wider sustainability targets, is the main goal for the building industry for the coming decades. The Zero building does not produce any CO_2 emissions locally. However, special attention has to be paid to the CO_2 emissions of the primary electrical energy production from the grid. Electricity bills from the study period showed the following share of renewable and non-renewable electricity:
- 64.4% of renewable energy
- 35.6% of non-renewable energy, with an emission rate of 0,649 kgCO_2/kWh.

This results in annual CO_2 emissions of 58,759 kg for the Zero building, and a ratio for the gross area of the building of **3.35 kgCO_2/m^{2}y, 92%** lower than in a typical office building in the same climate zone.

However, this figure could be even lower if more PV panels contributed to the Zero building's renewable energy feed, or if the grid electricity had a greener source with lower carbon emissions. Both issues will be discussed further.

3.2. Neighbourhood scale monitoring

This research offers real data from the Ideo Campus, a non-residential neighbourhood composed of four buildings of different designs and types of use (office, educational and research) that coexist within the same campus and share a common 100% renewable district heating and cooling facility. To better visualize the data provided, energy flows are illustrated through Sankey diagrams, in which the width of the arrows is proportional to the flow rate and conserved quantities are shown within defined system boundaries.

Heating

In the production of heat, biomass is the dominant energy generation source, comprising 88% of the total. The solar thermal vacuum tubes on the roof of the Foundation building represent 5% of the total production. The geothermal heat pump produces the remaining 7%.

Figure 10. Heating production by systems and consumption by buildings.

Cooling

The energy produced by the geothermal cooling pump plays a very important role in meeting the demand for cold. This system covered 80% of the total annual consumption of cooling and the 16% is covered by an absorption machine that allows cold to be produced in summer from a supply of hot water generated by the solar thermal panels. The conventional chiller was only needed to cover the remaining 4% of the total cooling demand.

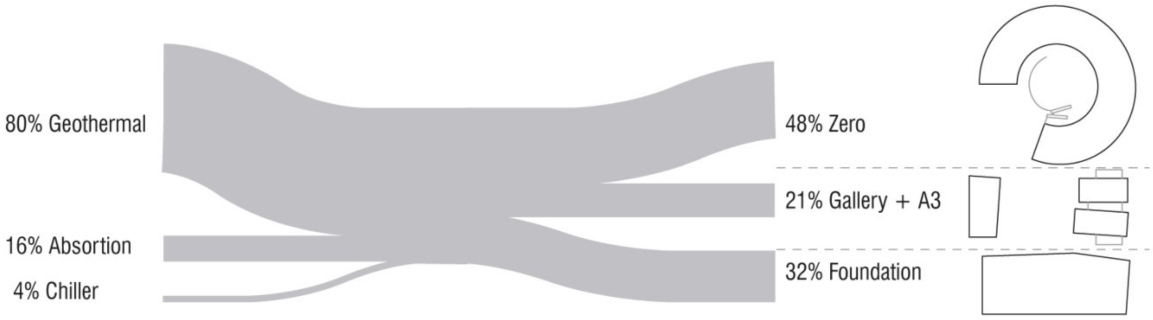


Figure 11. Cooling production by systems and consumption by buildings.

Photovoltaic roof

The integrated solar panels on the roof of the Zero building produce 273,380 kWh annually, which represents approximately 9% of the total final electricity demand of the whole campus.

A total of 50% of the electricity consumption of the neighbourhood corresponds to the Zero building. This can be partly attributed to the higher density of the installed equipment in comparison to the Foundation educational building, but mainly to the Data Centre situated in the building.

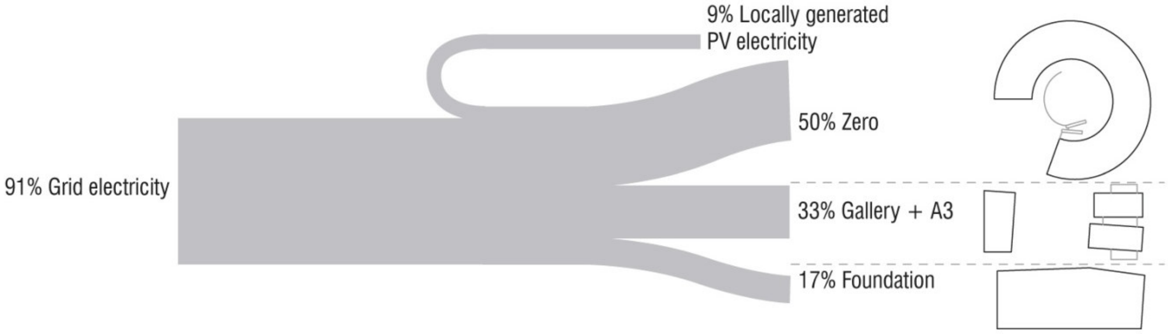


Figure 12. Sources of electricity generation and production and total consumption by buildings.

Indicators of total final energy consumption

The study analyses all the energy, both thermal energy and electricity, for the whole campus. Electricity represents 61% of all the final energy consumed in kWh per year, whereas heating and cooling were around 20% each.

Electricity consumption ratio was 57.48 kWh/m^{2}y, whereas the total mean consumption for the whole of the heated area of the Ideo buildings was 45.89 kWh/m^{2}y for heating and 43.57 kWh/m^{2}y for cooling.

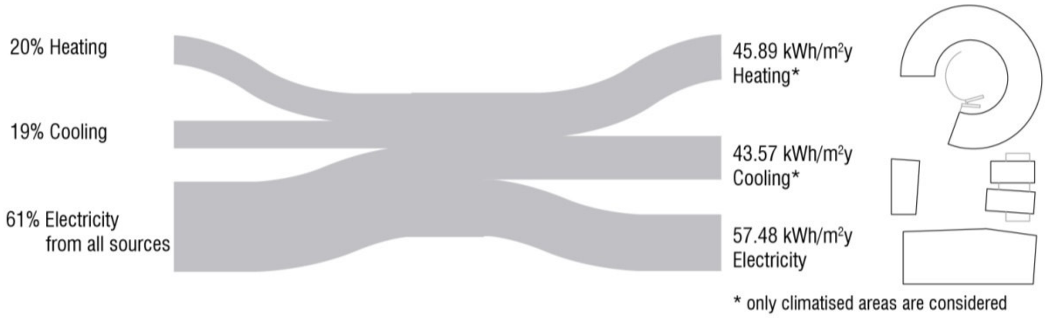


Figure 13. Annual total final energy consumption by energy type.

Considering the consumption by buildings, it is interesting to make the comparison between the Zero and Foundation buildings. The Zero building consumed only 35.74 kWh/m^{2}y for heating compared to the 64.78 kWh/m^{2}y for the Foundation building. This difference is largely due to the thermal input as a passive solar collector of the southern façade of the Zero courtyard, the building seemingly is not disadvantaged by having a large north-facing curtain wall. Both buildings have a similar cooling energy consumption, 39.91 and 37.17 kWh/m2y for Zero and Foundation respectively.

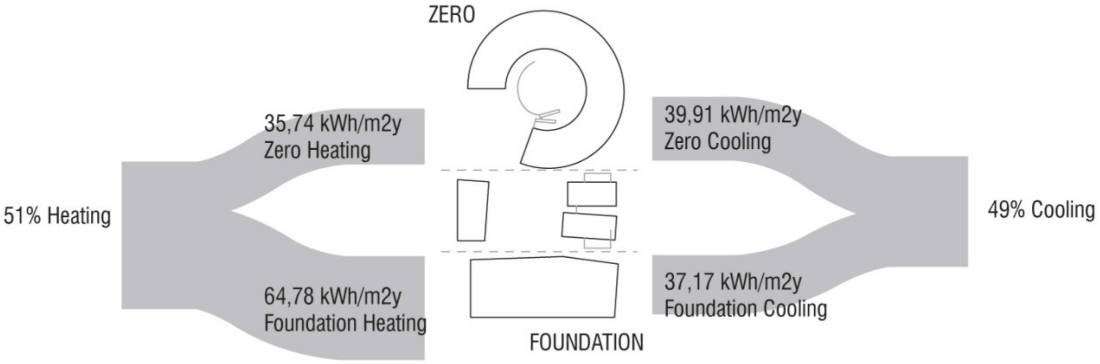


Figure 14. Total heating and cooling energy generated, and amount consumed by the Zero and Foundation buildings yearly per m^2.

CO2 emissions

Considering the entire energy generation mix necessary to cover the demand for heating, cooling, DHW and lighting, the only CO$_2$ emissions produced in Ideo are those corresponding to the electricity consumption of the district heating-cooling facility. If the contribution of the Zero building's photovoltaic roof is considered, the emissions due to the electricity for operational energy were only 0.29 kgCO2/m2y during the monitored year.

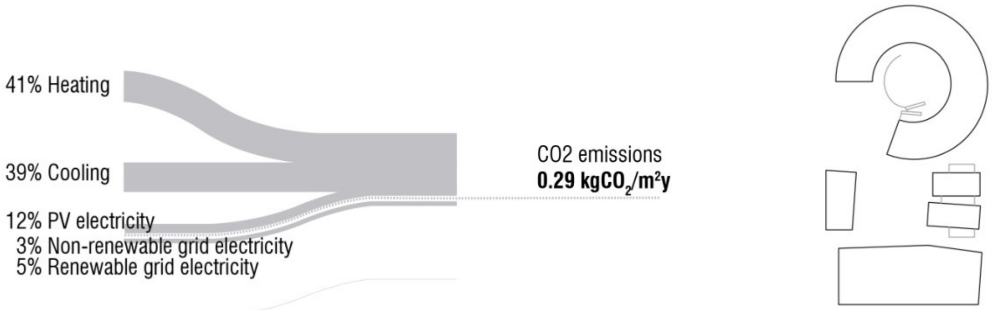


Figure 15. Energy consumed in the neighbourhood in% of kWh, and global ratio of CO2 emissions.

Finally, expanding the boundary of the study to the neighbourhood scale of the campus, energy inputs in the system included solar energy from the sun, 16% pellet biomass and 55% grid electricity supply from the grid. Total CO_2 emissions were 4,04 kgCO2/m2y, corresponding to the carbon emissions of the grid electricity.

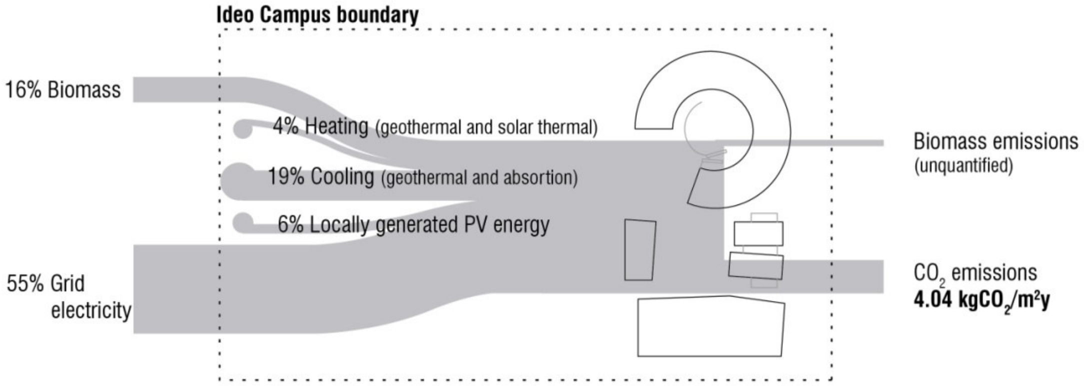


Figure 16. Energy flows considering the boundary of the Neighbourhood.

3.3. Sensitivity analysis to reduce carbon emissions

Sensitivity analysis determines how different values of an independent variable affect a particular dependent variable under a given set of assumptions. For this research, the following two hypotheses have been studied:

Zero consumes all the solar energy generated by its PV roof

This hypothesis is made considering that the energy produced by the PV roof is consumed locally by the building without sharing it to the neighbourhood. The results can provide a sense of the ability of a building of this kind to generate its own electricity on site. Integrating a sufficient PV solar panel roofing area into the architectural shape of a building could be a useful design parameter.

This approach is also considered an interesting design feature regarding the positive energy building (PEB) concept that is going to predominate in the coming years.(Magrini et al., 2020) (Ala-Juusela et al., 2016) (Cole & Fedoruk, 2015)

	Tot. Systems kWh/y	PV production kWh/y	PV self-sufficiency %
ZERO OPERATIONAL ELEC. ENERGY	368,049	273,380	**74.28%**

Table 3. Operational electrical energy self-sufficiency of the Zero building

On an annual basis, the Zero building is able to produce locally 74.28% of the electricity consumed by the technical systems of the building through the PV panels installed on its roof.

	Total grid energy kWh/y	PV panels kWh/y	TOTAL kWh/y	PV ratio %
ZERO FINAL ELEC. ENERGY	1,196,556	273,380	1,469,936	**18.60%**

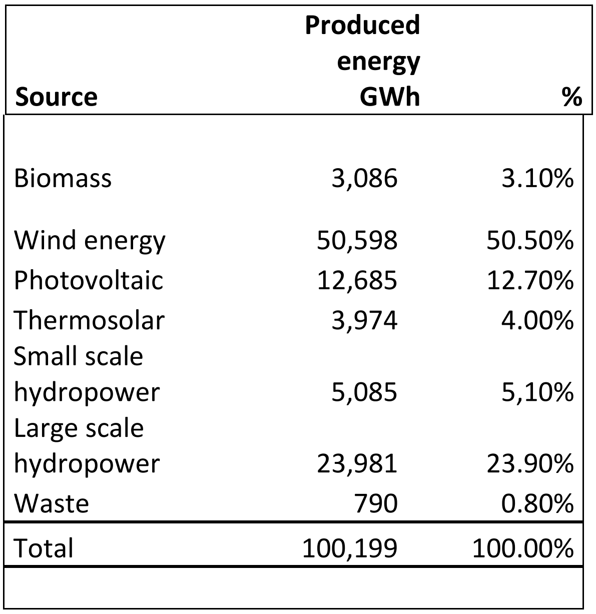
Table 4. Total electrical energy self-sufficiency of the Zero building

Considering the total amount of final energy,the Zero building produces 18.60% of the electricity it consumes (including the technical equipment, computers, etc.) on an annual basis.

Green electricity supply for the neighbourhood and the zero carbon emission goal.

The only carbon emissions at the Ideo Campus are produced from the electricity generated by the primary grid as there is no fossil fuel consumption on-site. This results in CO_2 emissions totalling 960.000 kg per year.

To achieve carbon neutrality, the intention is to replace the grid energy supplier with a green energy marketer that provides 100% green and renewable energy. The renewable grid electricity supply is published annually in Spain (CNMC, 2020) and the 2020 report showed the following share:



Source	**Produced energy GWh**	**%**
Biomass	3,086	3.10%
Wind energy	50,598	50.50%
Photovoltaic	12,685	12.70%
Thermosolar	3,974	4.00%
Small scale hydropower	5,085	5,10%
Large scale hydropower	23,981	23.90%
Waste	790	0.80%
Total	100,199	100.00%

Table 5. Annual 100% renewable electricity share by energy source in Spain (2020).

At the time the research took place it was still not possible to assure such a supply due to commercial issues, but it will soon be a real possibility as the demand for green energy and its share of the energy grid increases. In that case, it will be possible to certify that the impact of carbon emissions of the overall project is zero.

4. Conclusions

Since the end of 2020 all new buildings in the European Union have to comply with the NZEB standard as defined by each member country. In 2018, a new version of the EPBD UE2018/844 was released that aims to reduce greenhouse gas emissions by at least 40% by 2030 compared to 1990. To meet this goal, EU programs promote the NZEB design and its evolution, namely the positive energy building (PEB) model. PEBs represent an enhancement of NZEBs and consist of buildings that produce more energy than they consume. The strategies to achieve PEBs will be based on the knowledge gained from the NZEB buildings that are already in use. The 2010s were synonymous with the first generation of NZEBs, and it is time to assess the real performance of sample buildings to meet the future challenges until 2030.

Most of the studies into low carbon and zero energy buildings are based on simulations, and there is a lack of studies that investigate their real monitoring data. Most of the published case study buildings are still dependent on fossil energy sources, and there is a high diversity of climate situations. Climate and typology are key to correctly understanding the performance of a building. A common methodology for the comparative analysis of buildings is needed with a finer classification in order to draw better conclusions that can be applied to future projects.

This paper presents end-use energy data from the **Zero building**, an exemplary NZEB office building integrated in a low carbon neighbourhood. The building achieved both Breeam Excellent and Leed Gold Energy and Environmental Design certifications. The building shares a zero-emission district heating-cooling facility with three other buildings that use **100% renewable energy sources**: biomass, geothermal and solar thermal**.** A one-year study of the occupied Zero building demonstrated that the photovoltaic roof provides a degree of **self-sufficiency** of **74,3%** for the operational electric energy. The carbon footprint is only **3.35 $kgCO_2/m^2y$**, **92%** lower than in a typical office building situated in the same climate zone.
Discrepancies in simulated and real energy consumption have been observed and are attributed to higher passive solar gains and occupants' indoor temperature demands. Differences between the buildings of the campus correspond to different designs and patterns of use.

Sankey diagrams are used to illustrate the energy flows, and energy inputs at the scale of the Ideo Campus include solar energy, 16% of pellet biomass and 55% of grid electricity supply from the grid. Total CO_2 emission outputs were **4.04 $kgCO_2/m^2y$**, corresponding to the carbon emissions of the grid electricity.

This case study shows that nowadays low carbon neighbourhoods of non-residential mixed-use buildings are possible without fossil fuels and highlights a possible path for the next generation of positive energy buildings (PEB), which will achieve energy self-sufficiency at the neighbourhood scale.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or non-profit sectors.

Declaration of interest statement

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no financial support for this work that could have influenced its outcome.

References

Ahmed, K., Yoon, G., Ukai, M., & Kurnitski, J. (2019). How to compare energy performance requirements of Japanese and European office buildings. *E3S Web of Conferences*. https://doi.org/10.1051/e3sconf/201911103038

Ala-Juusela, M., Crosbie, T., & Hukkalainen, M. (2016). Defining and operationalising the concept of an energy positive neighbourhood. *Energy Conversion and Management*, *125*, 133–140. https://doi.org/10.1016/j.enconman.2016.05.052

Amaral, A. R., Rodrigues, E., Rodrigues Gaspar, A., & Gomes, Á. (2018). Review on performance aspects of nearly zero-energy districts. In *Sustainable Cities and Society* (Vol. 43, pp. 406–420). Elsevier Ltd. https://doi.org/10.1016/j.scs.2018.08.039

Ascione, F., Bianco, N., Böttcher, O., Kaltenbrunner, R., & Vanoli, G. P. (2016). Net zero-energy buildings in Germany: Design, model calibration and lessons learned from a case-study in Berlin. *Energy and Buildings*. https://doi.org/10.1016/j.enbuild.2016.10.019

ATELIER | Positive Energy Districts. (n.d.). Retrieved May 9, 2021, from https://smartcity-atelier.eu/?cn-reloaded=1

Attia, S. (2016). Towards regenerative and positive impact architecture: A comparison of two net zero energy buildings. *Sustainable Cities and Society*. https://doi.org/10.1016/j.scs.2016.04.017

Barrutieta, X. (2010). *Evaluacion de la sostenibilidad en la escala del microurbanismo. Las Células Urbanas.* 1–10.

BPIE. (2010). Nearly Zero Energy Buildings definitions across Europe. *Energy*.

CNMC - Comisión Nacional de los Mercados y la Competencia. (2020). *INFORMACIÓN ESTADÍSTICA DEL SISTEMA DEGARANTÍAS DE ORIGEN RELATIVO A LA ENERGÍA PRODUCIDA EN ELAÑO 2020*. https://gdo.cnmc.es/CNE/resumenGdo.do?informe=garantias_etiquetado_electricidad

Cole, R. J., & Fedoruk, L. (2015). Shifting from net-zero to net-positive energy buildings. *Building Research and Information*, *43*(1), 111–120. https://doi.org/10.1080/09613218.2014.950452

Deng, S., Wang, R. Z., & Dai, Y. J. (2014). How to evaluate performance of net zero energy building - A literature research. In *Energy*. https://doi.org/10.1016/j.energy.2014.05.007

European Parliament. (2010). The Energy Performance of Buildings Directive. *Official Journal of the European Union*, *L*(153), 13–35. http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:18.6.2010#1

EXCESS | Home. (n.d.). Retrieved May 9, 2021, from https://positive-energy-buildings.eu/

Feng, W., Zhang, Q., Ji, H., Wang, R., Zhou, N., Ye, Q., Hao, B., Li, Y., Luo, D., & Lau, S. S. Y. (2019). A review of net zero energy buildings in hot and humid climates: Experience learned from 34 case study buildings. *Renewable and Sustainable Energy Reviews*, *114*. https://doi.org/10.1016/j.rser.2019.109303

Flodberg, K., Blomsterberg, Å., & Dubois, M. C. (2012). Low-energy office buildings using existing technology: Simulations with low internal heat gains. *International Journal of Energy and Environmental Engineering*. https://doi.org/10.1186/2251-6832-3-19

Garde, F., & Donn, M. (2014). IEA SHC Task 40 / EBC Annex 52 Towards Net Zero Energy Solar Buildings: A review of 30 Net ZEBs case studies. *International Energy Agency (IEA)*, *May*, 130. http://www.enob.info/en/net-zero-energy-buildings/map/

Harkouss, F., Fardoun, F., & Biwole, P. H. (2018). Optimization approaches and climates investigations in NZEB—A review. *Building Simulation*, *11*(5), 923–952. https://doi.org/10.1007/s12273-018-0448-6

Hyde, R., Rajapaksha, U., Rajapaksha, I., Riain, M. O., & Silva, F. (2012). A Design Framework for Achieving Net Zero Energy Commercial Buildings. *Buildings and Energy*, *March 2015*, 8.

IDAE. (2021). *LIDER-CALENER spanish energy certification software*.

Irulegi, O., Torres, L., Serra, A., Mendizabal, I., & Hernández, R. (2014). The Ekihouse: An energy self-sufficient house based on passive design strategies. *Energy and Buildings*, *83*, 57–69. https://doi.org/10.1016/j.enbuild.2014.03.077

Is the Primary Energy Factor the right indicator for determining the energy performance of buildings? | BPIE - Buildings Performance Institute Europe. (2017). https://www.bpie.eu/publication/the-role-of-the-primary-energy-factor-pef-in-determining-the-energy-performance-of-buildings/

Jones, P., Hou, S. S., & Li, X. (2015). Towards zero carbon design in offices: Integrating smart facades, ventilation, and surface heating and cooling. *Renewable Energy*.

https://doi.org/10.1016/j.renene.2014.06.027

Jung, N., Paiho, S., Shemeikka, J., Lahdelma, R., & Airaksinen, M. (2018). Energy performance analysis of an office building in three climate zones. *Energy and Buildings*. https://doi.org/10.1016/j.enbuild.2017.10.030

Kurnitski, J., Achermann, M., Gräslund, J., Hernandez, O., & Zeiler, W. (2013). nZEB case studies. In *Green Energy and Technology* (Issue 9781447156093, pp. 135–176). Springer Verlag. https://doi.org/10.1007/978-1-4471-5610-9_8

Lenoir, A., Baird, G., & Garde, F. (2012). Post-occupancy evaluation and experimental feedback of a net zero-energy building in a tropical climate. *Architectural Science Review*, *55*(3), 156–168. https://doi.org/10.1080/00038628.2012.702449

Magrini, A., Lentini, G., Cuman, S., Bodrato, A., & Marenco, L. (2020). From nearly zero energy buildings (NZEB) to positive energy buildings (PEB): The next challenge - The most recent European trends with some notes on the energy analysis of a forerunner PEB example. *Developments in the Built Environment*. https://doi.org/10.1016/j.dibe.2020.100019

Mavrigiannaki, A., Pignatta, G., Assimakopoulos, M., Isaac, M., Gupta, R., Kolokotsa, D., Laskari, M., Saliari, M., Meir, I. A., & Isaac, S. (2021). Examining the benefits and barriers for the implementation of net zero energy settlements. *Energy and Buildings*, *230*, 110564. https://doi.org/10.1016/j.enbuild.2020.110564

Mavrigiannaki, Angeliki, Gobakis, K., Kolokotsa, D., Kalaitzakis, K., Pisello, A. L., Piselli, C., Gupta, R., Gregg, M., Laskari, M., Saliari, M., Assimakopoulos, M.-N., & Synnefa, A. (2020). Measurement and Verification of Zero Energy Settlements: Lessons Learned from Four Pilot Cases in Europe. *Sustainabiliry*, 16. https://doi.org/10.3390/su12229783

Moran, P., Goggins, J., & Hajdukiewicz, M. (2017). Super-insulate or use renewable technology? Life cycle cost, energy and global warming potential analysis of nearly zero energy buildings (NZEB) in a temperate oceanic climate. *Energy and Buildings*, *139*(2017), 590–607. https://doi.org/10.1016/j.enbuild.2017.01.029

Musall, E., Weiss, T., Voss, K., Lenoir, A., Donn, M., Cory, S., & Garde, F. (2016). *Net Zero Energy Solar Buildings: An Overview and Analysis on Worldwide Building Projects*. https://doi.org/10.18086/eurosun.2010.06.16

Newton, P. W., & Tucker, S. N. (2010). Hybrid buildings: a pathway to carbon neutral housing. *Architectural Science Review*, *53*(1), 95–106. https://doi.org/10.3763/asre.2009.0052

Pan, W., & Li, K. (2016). Clusters and exemplars of buildings towards zero carbon. *Building and Environment*, *104*, 92–101. https://doi.org/10.1016/j.buildenv.2016.04.027

Peng, C., Huang, L., Liu, J., & Huang, Y. (2015). Design and practical application of an innovative net-zero energy house with integrated photovoltaics: a case study from Solar Decathlon China 2013. *Architectural Science Review*, *58*(2), 144–161. https://doi.org/10.1080/00038628.2015.1011075

Pless, S., & Torcellini, P. (2010). Net-Zero Energy Buildings : A Classification System Based on Renewable Energy Supply Options. *Contract*. https://doi.org/10.2172/983417

Polly, B., Kutscher, C., Macumber, D., & Schott, M. (2016). From Zero Energy Buildings to Zero Energy Districts. *2016 ACEEE Summer Study on Energy Efficiency in Buildings*, *August*, 1–16. https://www.researchgate.net/publication/307955877_From_Zero_Energy_Buildings_to_Zero_Energy_Districts/figures?lo=1

Sartori, I., & Hestnes, A. G. (2007). Energy use in the life cycle of conventional and low-energy buildings: A review article. *Energy and Buildings*. https://doi.org/10.1016/j.enbuild.2006.07.001

Sartori, Igor, Napolitano, A., & Voss, K. (2012). Net zero energy buildings: A consistent definition framework. *Energy and Buildings*. https://doi.org/10.1016/j.enbuild.2012.01.032

Sudhakar, K., Winderla, M., & Priya, S. S. (2019). Net-zero building designs in hot and humid climates: A state-of-art. *Case Studies in Thermal Engineering*. https://doi.org/10.1016/j.csite.2019.100400

Torcellini, P., Pless, S., Deru, M., & Crawley, D. (2006). Zero Energy Buildings: A Critical Look at the Definition. *ACEEE Summer Study Pacific Grove*, 15. http://www.nrel.gov/docs/fy06osti/39833.pdf

Wikipedia (a). (2014). *Oceanic climate*. 1. http://en.wikipedia.org/wiki/Oceanic_climate

World Green Building Council. (2015). Health, Wellbeing & Productivity in Offices: The next chapter for green building. In *World Green building Council*.

Zero-Plus. (n.d.). Retrieved May 9, 2021, from http://www.zeroplus.org/

Zhou, Z., Feng, L., Zhang, S., Wang, C., Chen, G., Du, T., Li, Y., & Zuo, J. (2016). The operational performance of “net zero energy building”: A study in China. *Applied Energy*. https://doi.org/10.1016/j.apenergy.2016.05.093

Captions for the graphics and tables

Graphical Abstract. Energy analysis at the Ideo Campus boundary, and corresponding CO_2 emissions.
Figure 1. European NZEB model introduction and the challenge of its evolution towards PEB.
Figure 2. Front façade of the Zero building.
Figure 3. Inclined PV roof of the Zero building.
Figure 4. Floor plan of the first floor of the Zero building.
Figure 5. Building section from the symmetry axis of the Zero building.
Figure 6. Triangulated curtain wall composed of opaque, translucent, and transparent elements represented on the unfolded cylindrical façade of the Zero building. The design responds both to the incident solar radiation and use of the interior space in the building.
Figure 7. Inner view of the south facing circulation gallery where different elements of the curtain wall can be observed.
Figure 8. Energy generation, technologies, storage, distribution and consumption for the Ideo Campus.
Figure 9. Simulation of accumulated direct solar radiation for the Zero building during the summer months. The colour bar scale shows a gradient for Wh/m^2 units.
Figure 10. Heating production by systems and consumption by buildings.
Figure 11. Cooling production by systems and consumption by buildings.
Figure 12. Sources of electricity generation and production and total consumption by buildings.
Figure 13. Annual total final energy consumption by energy type.
Figure 14. Total heating and cooling energy generated, and amount consumed by the Zero and Foundation buildings yearly per m^2.
Figure 15. Energy consumed in the neighbourhood in% of kWh, and global ratio of CO2 emissions.
Figure 16. Energy flows considering the boundary of the Neighbourhood.

Table 1. Buildings at the Ideo Campus and their floor area.
Table 2. Electrical energy consumption of the building technical systems for liveability conditions at the Zero building distributed by systems according to 2010/31/EU
Table 3. Operational electrical energy self-sufficiency of the Zero building Directive.
Table 4. Total electrical energy self-sufficiency of the Zero building
Table 5. Annual 100% renewable electricity share by energy source in Spain (2020).