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Title

Energy balance and photovoltaic integration in positive energy buildings (PEB). Design and performance in built office case studies.

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Net zero energy building (NZEB); Positive energy building (PEB); case studies; energy self-sufficiency; PV integration

Abstract

Solar design will be reshaping the architecture as one way to address the global climate crisis and the reduction of fossil fuel consumption. This paper analyses the current definition of Positive Energy Building (PEB) and a selection of both NZEB and PEB built projects with real monitored data, discussing their design features and potential for achieving positive energy balance.

The research aims to assess an optimal ratio between PV area in both roof and façade, net floor building area and achieved self-sufficiency ratios in office buildings. The study shows that most of the buildings' PV systems have an area equal to 10-20% of the total building's net floor area. Buildings that have PV to area ratio from 13 to 20% are self-sufficient from 100 to 150%. PV installation in the façades results decisive for reaching positive energy balance. The relation of the PV system installed on the façade to PV system on the roof is from 50 to 57 % for the studied buildings. Buildings located in sites with higher GHI tend to have lower PV area ratios and a ratio of 20% or more is valid for all the studied sites to achieve electrical energy self-sufficiency.

1. Introduction

1.1 The relevance of PEB within European regulatory framework

In response to the environmental problems and in line with the objectives of the Paris agreement, the European Union is committed to developing a sustainable, competitive, secure and decarbonized energy system by 2050. The goal of the decarbonization of the building stock by 2050 is set. Buildings are responsible for approximately 36 % of all CO2 emissions in the Union and for around 40% of energy consumption (European Commission 2020b). Therefore, Member States should seek a cost-efficient equilibrium between decarbonizing energy supplies and reducing final energy consumption (European Parliament and Council of the European Union 2018b). One of the applied measures is that from 2021 all new buildings and deep renovations should be at least nearly-Zero Energy Building (nZEB) standard defined by each Member State, as required by the Energy Performance of Building Directive (EPBD) (EU 2018/844). A NZEB is defined as a building with a very high energy performance that covers as much as possible the demand of the building by renewable energy sources, produced on-site or nearby (D'Agostino et al. 2021).

The Green Deal supports the renovation wave initiative and promotes the consumer empowerment in order to help EU countries to tackle energy poverty (European Commission 2020c). The Clean Energy Package introduces renewable energy communities (European Parliament and Council of the European Union 2018a) and promotes renewable energy prosumers (energy producers and consumers) allowing the households, communities and business become clean energy producers. This communities are now also integrated in national regulations of Member States (Inês et al. 2020), (Build up 2021). Therefore, along with the spread of renewable energy, the decentralized energy production is increasing. It offers cost-savings, efficiency gains and increased power capacity among other benefits (Kumar and Cao 2021).

In this context, positive energy buildings can be a new target. Positive energy buildings (PEBs) contribute to EU's target for decarbonization of the energy supply and shift from fossil fuels to RES (Ala-Juusela and ur Rehman 2020). They produce more energy than they consume on annual basis. The surplus energy can support other buildings and, if the energy needs are balanced, it leads to energy independence of whole building stocks (Magrini et al. 2020). This goes in line with consumers empowering strategy increasing the affordability of REN. This way, the PEB concept goes beyond the NZEB in on-site renewable energy generation and in such areas as carbon and greenhouse gases emissions reduction, cost-effectiveness and the utility grid support (Kumar and Cao 2021).

A wide range of positive energy initiatives were funded by Horizon 2020 funding program (Magrini et al. 2020), (Brozovsky, Gustavsen, and Gaitani 2021). For example, the Program on Positive Energy Districts and Neighbourhoods (PED Program) established in 2018 supports the planning, deployment and replication of 100 'Positive Energy Districts' across Europe by 2025 in the framework of JPI Urban Europe program. Innovation project Positive City ExChange (+CityxChange) is another project to develop and deploy Positive Energy Blocks, Districts, and Positive Energy Cities (Ahlers et al. 2019), (Gall et al. 2020). Among other projects, syn.ikia, SPARCs ((Uspenskaia et al. 2021)) and ASSET (de Radiguès, De Vos, and Bosso 2020) are also worth mentioning.

At building scale, the EXCESS project aims to demonstrate how nearly-zero energy buildings can be successfully transformed into positive energy buildings (PEBs) with cases in four different European Climatic Zones (Nordic, Continental, Mediterranean, and Coastal) (as stated on the EXCESS project website). Cultural-E is another EU-funded project, which aims to define modular and replicable solutions for Plus Energy Buildings (PEBs), accounting for climate and cultural differences, while engaging all key players involved in the building life cycle. The project is developing European Climate and Cultural Atlas for Plus Energy Building Design (2CAP-Energy Atlas) (Passer et al. 2016) that will help to define appropriate solutions for PEB based upon local climate and cultural factors.

The Horizon Europe and LIFE programs keep supporting energy efficiency projects under the new Multi-annual Financial Framework 2021-2027, as stated on the European Commission website in July of 2022. Consequently, the relevance of the PEB topic for the European Commission is evident.

As for national level, some countries included positive energy concepts in their National Energy and Climate Plans 2021-2030 (NECP).

For instance, Austria promotes “Building blocks for energy systems of the future” initiative as part of its Integrated National Energy and Climate Plan (Federal Ministry for Sustainability and Tourism Republic of Austria 2019). The following ‘building blocks’ are plus energy areas that generate renewable energy locally. The Austrian Federal Ministry of Transport, Innovation and Technology (BMVIT) is committed to the implementation of positive energy districts (or neighborhoods) in the framework of **“**City of Tomorrow” program. As of July 2022, the program stated on its website that "Building of Tomorrow" and its second phase "Building of Tomorrow Plus" are creating the technological basis for the building of tomorrow, especially for the plus-energy house. Similarly, positive energy districts and smart power grids are set among priorities in Belgian NECP (Federal Government of Belgium et al. 2019).

In addition, several PEB definitions and standards are being developed and promoted within different European countries; some of them are part of the legal framework.

In France, the Law on Energy Transition for Green Growth (LTECV, 2015) includes positive energy and high environmental performance buildings promotion among other measures (“Loi No 2015-992 Du 17 Août 2015 Relative à La Transition Énergétique Pour La Croissance Verte [Law No. 2015-992 of August 17, 2015 on Energy Transition for Green Growth]” 2015), (Grantham Institute 2015). Following the LTECV and the Paris agreement, French authorities developed a new ambitious regulation that combines energy performance and environmental requirements and aims to promote positive energy buildings and low carbon buildings. A testing scheme called “E+ C-“(standing for Energy plus Carbon minus), for voluntary developers, started in late 2016 (Bordier and Rezaï 2016). A new BEPOS label has four different levels based on the energy consumption and two on the carbon footprint. The fourth level (minimum for BEPOS+ effinergie 2017) matches the positive energy building (meaning that the energy performance is lower than zero) (Ministère de L’Environnement, de L’Energie et de la Mer and Ministère du Logement et de l’Habitat durable 2016), (effinergie 2017). As claimed on the Positive-Energy and Low Carbon Buildings website in July 2022, future regulations will make positive energy buildings, or “BEPOS”, the new nationwide norm.

In Germany, the Federal Ministry of the Interior for Building and Homeland promotes The Efficiency House Plus (Erhorn-Kluttig, Erhorn, and Reiß 2015). As of July, 2022, the Zukunft Bau states that the Efficiency House Plus network encompasses 44 buildings (housing and educational facilities) which are being monitored for academic analysis.

In Norway, Powerhouse Paris Proof is a new standard for the buildings of the future, based on the Paris Agreement’s 1.5-degree target. As listed on the Powerhouse website, the standard along with CO2 emissions limits uses energy positive buildings definition as a basis for energy production. Powerhouse is a collaboration between the property company Entra, the entrepreneur Skanska, the environmental organization ZERO, Snøhetta architecture and design office, and the consulting company Asplan Viak.

1.2 State of art of PEBS

To assess the state of art of the topic and identify PEB concept definition, as well as performance assessment methodologies, a literature review has been carried out. The search engine Science Direct was used to identify the most relevant papers and documented case studies in the field. In July of 2022, 17 publications with ‘’positive energy building’’ term in their title or among the key words can be found. “Plus-energy building” term adds 14 publications. Some papers distinguish the term “positive energy building” from “plus energy building”, understanding the first as a building with positive energy balance and the second as more holistic concept that includes also other aspects such as indoor comfort (Hawila et al. 2022). However, most of the found studies make no distinction between the two.

Including other popular PEB related keywords such as, plus-energy house (4), positive energy block (2) and district (5 results), the total number of publications on PEB on Science Direct becomes 42. Studies focused solely on innovative solutions with possible application in PEBs are not included.

A range of publications consider the state of art of PEBs, or assess PEBs as NZEB's evolution ((Kumar and Cao 2021), (Magrini et al. 2020), (Cole and Fedoruk 2015), (Kolokotsa et al. 2011), (Marino et al. 2019)). Others analyze the positive energy concept and its design implications at block, district or community scale ((Brozovsky, Gustavsen, and Gaitani 2021), (Blumberga et al. 2020), (Good, Ceseña, and Mancarella 2017), (Alpagut, Akyürek, and Mitre 2019), (Lindholm, Rehman, and Reda 2021), (Moreno et al. 2021), (Rueda Castellanos and Oregi 2021), (Bauwens and Devine-Wright 2018), (Soutullo et al. 2020)). Another group of papers discuss solutions for different climate zones ((Firlag 2019), (Dávi et al. 2016), (Bojić et al. 2011), (Franchini, Brumana, and Perdichizzi 2019), (Rehman et al. 2019), (Dabaieh and Johansson 2018)). Constructional considerations are also present in some other researches ((Pataky et al. 2014), (Lydon et al. 2017)). Finally, specific PEB related topics like passive design strategies (Rodriguez-Ubinas et al. 2014), and the performance of the solar energy harvesting via PV or BIPV (Zomer et al. 2020) are identified significant topics of research to achieve the PEB goal. Those investigations that collect data from real case studies have been considered of special interest.

Despite of the rising popularity of the PEBs, currently it has no universal definition. Several definitions proposed in the literature are analyzed for the purpose of this study. A generic definition states that building is plus energy when it produces more energy from renewable energy sources, over the course of a year, than it needs for heating, cooling, ventilation, domestic hot water (DHW) and auxiliary systems (Kumar and Cao 2021). Including all energy uses in the balance ensures that the building has an energy production surplus to be shared with other buildings (Hawila et al. 2022). Some authors view PEB as a NZEB but more efficient, so it produces more energy than consume, leaving users with extra energy to employ in other ways, such as powering mobile devices, electric tools or even the electric car (Magrini et al. 2020). Positive energy balance means that the annual electrical energy surplus fed-in to the grid is greater than the annual electrical energy imported from the grid (Bojić et al. 2011).

The excess electric energy is sent to the grid and this annual surplus fed-in to the grid is greater than the annual electrical energy imported from the grid. The purpose and the distribution of the surplus energy is also important (Cole and Fedoruk 2015). In addition, energy efficiency level should be high, so a balance between the installation of renewable energy systems and energy savings should be found. The energy demand is to be reduced and the renewable energy production increased (Firlag 2019). The cost-effectiveness, indoor comfort can also be taken into account.

Therefore, PEB concept focuses on a holistic approach to high energy performance rather than on a simple generation and export of the excess energy. As explained previously, there are different PEBs definitions, some of which are centering on energy, exergy, other on cost, emission, or grid connection properties (Kumar and Cao 2021). This way, PEB relevant aspects can be identified and used as a base for a PEB concept framework. Among the main PEB aspects prevail balance contributions, physical boundary, the time span of evaluation, the metrics of evaluation and added value in sustainability and indoor comfort (Hawila et al. 2022).

The energy balance is mostly calculated as balance between energy consumption and generation, but can also be the grid import/export balance of energy. The most popular balance metrics are final and primary energy, the primary energy balance is utilized more (Hawila et al. 2022). However, the definition can include also carbon emissions balance rather. For instance, some certifications' databases such as Observatoire BBC (Effinergie) use the metrics of primary energy balance and carbon emissions. The energy balance can be accounted during one year of building's operation ((Marino et al. 2019), (Firlag 2019), (Dabaieh and Johansson 2018), (Bojić et al. 2011)) or for the whole lifespan of the building, as in Powerhouse definition.

1.3 European PEB existing standards

This paper focuses on building scale of positive energy concept, thus four standards of positive energy buildings were selected. Along with the EXCESS definition, three other definitions and standards are considered and compared in the table 1. The BEPOS E+C- is a French legal definition of an energy-positive and low-carbon emitting building. PEBs correspond to "Energy 4" level. Efficiency House Plus is an official definition by German Federal Ministry of Building. Finally, Powerhouse is a Norway standard.

The above-mentioned relevant aspects (the physical boundaries, the balance contributions, and the time span of balance evaluation) are compared in the selected PEB definition and summarized in table 1.

The definition elaborated by the EXCESS Consortium covers most of the features mentioned in other definitions. According to EXCESS, a positive energy building (PEB) is an energy efficient building that produces more energy than it uses via renewable sources, with high self-consumption rate and high energy flexibility, over a time span of one year (Ala-Juusela and ur Rehman 2020). A high quality indoor environment is an essential element in the PEB, maintaining the comfort and well-being of the building occupants. The PEB can also integrate technologies like electric vehicles with the motivation to maximize the onsite consumption and share the surplus renewable energy. EXCESS definition and concept go in line with the ideas on citizen empowerment and user comfort.

First, the country, authors and key principles with added value of a standard are described. Then time span of evaluation, type of building and physical boundary of each standard is stated. The EXCESS definition is valid for all new and retrofit buildings, while other standards are applied only to new buildings in urban area (BEPOS+ effinergie 2017 (E4 C1/C2)), or residential and educational buildings (Efficiency House Plus). The Powerhouse standard has office and educational buildings mostly. The boundary is either the single building and its plot (EXCESS, Efficiency House Plus), either is no specified. The balance is accounted between energy consumption and renewable energy generation. Efficiency House Plus also accounts annual final energy demand. However, Powerhouse standard requires the building to cover the total embodied energy used for the production and transportation of the building materials, as well as the energy to renovate and demolish the building. As for the added value of the certified building, the four standards take into account the environmental performance. BEPOS+ effinergie 2017 and EXCESS also pay attention to economic evaluation.

Table 1. Selected PEB definitions comparison

		EXCESS definition	**BEPOS+ effinergie 2017 (E4 C1/C2)**	**Efficiency House Plus**	**Powerhouse standard**
Country		EU	France	Germany	Norway
Authors		The EXCESS team and partners	The government and the Executive Council for Construction	Federal Ministry of Building	Companies coalition including Skanska, Snøhetta, Entra and other[1]
Key principles[2]	Energy performance	X	X	X	X
	Environmental performance	X	X	*	X
	Economic evaluation	X	X		
	Social Perspective	X			
	Technology Perspective	X			
Time span of evaluation		yearly on-site energy ratio (OER)	Annual balance during the building's life cycle, 50 years for all buildings		Annual balance over the lifetime (60 year operational phase)

Type of buildings	Any (new/retrofit)	New/ under construction in a metropolitan area in compliance with France's 2012 energy efficiency standards	Residential, educational mostly, that comply with the Energy Saving Ordinance. Refurbished buildings initiative currently testing	Office, educational mostly, new and retrofit
Boundary of the system	the focus is on the single building on site renewable energy	Local area	Plot boundary (boundary of the property as in land registration)	Not specified, on or near building
Performance level and balance	energy efficient building that produces more energy than it uses via renewable sources, with high self-consumption rate and high energy flexibility, over a time span of one year	Negative level of overall energy use, contribution to the production of RE for the local area and low carbon and GHG emissions during the life cycle, including construction Bbio (energy needs), Cep (energy consumption) and BEPOS rating (the energy consumed by all sources associated with the building)	a building has both a negative annual primary energy demand ($\sum Qp < 0$ kWh/m2a) and a negative annual final energy demand ($\sum Qe < 0$ kWh/m2a)	A construction that generates more renewable energy than the total amount of the energy required to sustain daily operations and to build, covering the total embodied energy used for the production and transportation of the building materials, as well as the energy to renovate and demolish the building
Research, data collection	EXCESS project	Observatory collects data of the operations, feedback and best practices for the drafting of future legislation.	"Future Building" Research Initiative (ZEBAU), also offers consulting services. Building monitoring program	1st Nordic conference on Zero Emission and Plus Energy Buildings, 2019
Legal context	EU energy regulatory framework (EPBD; 2010/31/EU, EED; 2012/27/EU, Clean Energy Package, New rules for the internal market in electricity, Green Deal)	2015 National Low-Carbon Strategy RT 2012 RE 2020	The Energy Saving Ordinance (EnEV), the Act on the Promotion of Renewable Energies in the Heat Sector (EEWärmeG)[3]	
Specifications	A high quality indoor environment, comfort and well-being of the occupants, also integration of the technologies like electric vehicles	Requirements both on the performance of its envelope, its equipment, and on the construction quality and ecomobility potential (assessment of the energy consumption generated by the movements of building users).	The ratio of **self-used renewable energy** generated on site should be as high as possible	
Participation		Self-assessment, or assessment by a certification body providing guidance during the early stages of the project.	The standardised calculations can be carried out using a free online tool	At least two of the affiliated companies are involved during construction and to monitor the project after completion

Certification label		The E+C- certification label that is only awarded by one of 5 certification bodies approved by the government Bepos + Effinergie 2017	Efficiency House Plus standard energy performance certificate	Powerhouse standard
Software tools		Several software tools are approved for energy performance evaluation	The standardised calculations for an Efficiency House Plus can be carried out using a free online tool	
References	(Ala-Juusela and ur Rehman 2020)	(Ministère de la Transition Ecologique et Solidaire and Ministère du Logement et de l'Habitat durable n.d.)	(German Federal Ministry of the Interior, Building and Community (BMI) 2018)	Powerhouse website, 1st Nordic conference on Zero Emission and Plus Energy Buildings, 2019

*every Efficiency House Plus reduces both the fossil energy consumption and also greenhouse gas emissions, it's environment benefits average is of 50 kg/m²a of CO2 equivalents per square meter of heated net floor area
The project should be subject to an assessment of the energy consumption generated by the movements of building users (ecomobility potential).

1- the Skanska development company, the architecture firm Snøhetta, the real estate company Entra, the consulting firm Asplan Viak, the aluminium manufacturer Sapa Og and the environmental non-profit organization Zero
2- Energy performance (energy efficiency, consumption, demand reduction, production), Environmental performance (RES integration, CO2 GHG emissions reduction, circular economy), Economic evaluation (cost of technology and measurement, energy costs reduction, revenue streams from market transactions, business models viability, etc.) Social Perspective (user engagement, comfort and indoor environmental quality, energy security of supply, citizen empowerment),Technology Perspective (system interoperability, ICT solutions performance, compliance of functionality to the user requirements)
3- The planned Building Energy Law (GEG) is aimed at merging the Energy Saving Act (EnEG), (EnEV) and (EEWärmeG)

In addition, German Climate-positive award by DGNB is worth mentioning. The greenhouse gas emissions that result from the energy consumption of the building are compared with the emissions that are avoided by the building's own energy production at the site. The award is valid for the year in question. The certification system can be applied internationally, regardless of use, for all building types. The only requirement is that the building has been in use for at least one year. According to the DGNB website, there are three key elements to being climate-positive in the DGNB sense: first, high energy efficiency through smart building design, which is about making meaningful use of building technology and people knowing what they're doing; second, it's about using renewable energy; and third, it's about feeding self-produced energy back into the grid.

1.4 Structure and aim of the study

To achieve energy surplus, buildings need to reduce their energy demand as well as to produce energy on site. The research focuses in the photovoltaic integration in PEBs in office buildings and the possibility to achieve energy self-sufficiency. Most of the buildings systems are based on electricity that in PEBs should be produced from renewable sources, mostly from photovoltaics. Therefore, photovoltaic systems are indispensable and can be considered one of the factors that define the PEB's design. Office and administration buildings are used mainly during the solar hours of the day, which is an advantage to obtain energy self-sufficiency compared to other building typologies.

The main aim of this study is to provide ratios and aspects that could be useful for architects from early building design stages to integrate the photovoltaic system in the projects and help design effective self-sufficient PEB buildings. This way, the research is also applicable at the practitioner's field.

For this purpose, some relevant parameters have been selected and analyzed. For instance, the proportion of the photovoltaics area to the building area that could give an approximation to the required dimensions of the photovoltaic system. This ratio in different buildings of similar use and in similar climate conditions will be analyzed and compared in order to elaborate recommendations.

Climatic variation is a key factor in analyzing the performance of NZEB and PEB buildings. This research focuses on a specific climate zone that includes two climate types classified as Cfb and Dfb within the Köppen-Geiger scheme. The reason is that they cover most of Central and Western Europe, where PEB concept is being developed and where several interesting case studies are located.

Even in the same climatic zone, where the heating and cooling demands may be similar on average, variability in the latitude, altitude or orientation of the building may affect the PV performance of the buildings. Nonetheless, the energy self-sufficiency indicator and the PV area ratio indicators embrace these factors to demonstrate globally the success of the building design and its performance. Moreover, to address the possible impact of the natural conditions on the implementation of PV, the availability of solar resources at the studied locations is also taken into account. For this purpose, the global horizontal irradiation (GHI) variable is used, which is the sum of direct and diffuse irradiation components received by a horizontal surface. GHI is measured in kilowatt-hours per square meter (kWh/m2).

Moreover, the obtained ratio for PEBs' will be compared to NZEBs' ratio in order to study their potential upgrade towards PEBs. Other potentially useful ratios will be developed.

In addition, the paper assesses PEB design solutions implemented in the selected projects, as well as real energy data. A deeper knowledge of exemplary buildings could help the diffusion of PEB model. Measured and simulated data on energy consumption and generation are gathered and compared.

The first chapter considers PEB measures and uptake in Member States. A general outlook of the regulatory framework and the EU long-term vision is illustrated with PEB programs examples. In addition, some of the existing PEB concept definitions and standards are cited through a literature review, highlighting the key aspects related to the energy balance evaluation and overall PEB performance analysis. In the second chapter, the methodology and the case selection criteria are described. The third chapter introduces the case study projects assessing the selected buildings' added value beyond positive energy balance in reference to sustainability, quality of indoor environment and obtained degree of self-sufficiency. The fourth chapter contains a comparison and an a critical overview of the results. Finally, the conclusions and concepts interesting for further research are given.

2. Methodology

2.1 Methods and search process

The two main methods used in this research are documents analysis and cases comparison. The main sources of information about the current PEB situation in Europe are EU regulations, reports, directives, National Energy and Climate Plans and PEB national and EU funded projects. For the purpose of the PEB concept definition and performance analysis, as well as for the cases with monitored data, several studies (papers, conferences, thesis and programs reports that address PEB) had been found in Scopus, WOS and Google Scholar. Only papers that assess energy balance between generation and consumption at building scale were considered. Due to the fact that the PEB concept is still new there is a lack of investigations with real monitoring data. Therefore, most of the study cases were found on the official websites of ZEB, Observatoire BBC (Effinergie), EXCESS, Building of the Future, as well as on scientific conferences and energy certifications websites. This search focused mostly on European certifications' databases such as DGNB, klimaaktiv and Bepos that contain statistical information and projects with energy data with and are located mostly in oceanic and continental climate. Finally, the Construction21 web was used in order to obtain measured energy data.

2.2 Case selection parameters

The next parameters were taken into account to select the cases:

1. Positive annual energy balance
2. Only new construction buildings were considered (no renovation)
3. Office typology. However, administrative buildings were also taken into account.
4. Available measured or calculated energy data
5. Range of floor area between 800 and 20.000 m^2
6. Climate zone Cfb/ Dfb
7. No fossil fuel used, low carbon emissions

3. Case studies analyzed

According to EXCESS report, that identified 58 positive energy buildings (PEBs) in Europe over the past 11 years, office buildings are the most common PEB type, followed by single-family homes. Significant clusters can be found in countries such as France and Germany (Jäger 2020).

For the purpose of this study, case studies with available monitored energy data were searched and 13 high performance buildings were selected according to the established criteria. The selection includes buildings from different countries and different standard systems, all in compliance with the criteria defined in 2.2.

Nine of thirteen buildings have positive energy balance. Moreover, all the cases have an added value in environmental and indoor quality, described bellow in detail for each case.

The following PEBs have been selected:

3.1 Powerhouse Brattørkaia

Powerhouse Brattørkaia, an office building located in Trondheim, is the current flagship Positive Energy Building developed by Powerhouse - an alliance of private sector partners in Norway. By means of a local micro grid, the building supplies excess renewable energy to neighboring buildings, electric buses, cars and boats. Moreover, it is an interesting case to study solar energy harvest and store system, for the solar panels are located in the roof and in the façades. The measured PV production and calculated demand data by Skanska were found (Jenssen 2019). The building generates 120,7% more renewable energy than it consumes. Predicted energy demand data for year 2-60 of the building operation were considered.

3.2 Freiburg New City Hall

Freiburg New City Hall was the largest designed and built plus-energy building in Europe in 2019 (Réhault et al. 2019). Moreover, it has one of the largest solar glass facades in Europe. The energy supply is based on a low energy concept. Onsite energy is generated by a large Building Integrated Photovoltaic plant combined with photovoltaic-thermal combined collectors located at rooftop level. The distinctive curved design features a façade that consists of highly insulated panels equipped with 880 customized solar modules aligned towards the sun. The Fraunhofer Institut für Solare Energiesysteme (ISE) validates this project for its holistic characteristics of sustainability and integrity. Energy data measured in 2018 are available, and the first year of monitoring showed that the plus energy target was almost reached (98,8%).

3.3 Technology centre Aspern IQ

"Technology centre Aspern IQ" is a demonstration project in the Aspern Seestadt Wiens urban development area. It is one of the first commercially used plus-energy buildings in Austria and has klimaaktiv Gold certification and ÖGNB/TQB. The energy surplus is the result of combining passive house building standards with highly efficient building technologies as well as renewable energy sources. Moreover, numerous individual measures such as a superior add-on facade, used for energy production (PV), shading, or facade greening, a controlled mechanical ventilation depending on outside temperature and indoor air quality are combined. In addition, the waste heat from server rooms is used for space conditioning. The building participated in MonitorPlus project along with Windkraft Simonsfeld AG and other buildings, as well as in Cravezero project, so real measured data is available on MonitorPlus Leitprojekte and Cravezero websites.

3.4 Windkraft Simonsfeld AG

The new office building (headquarter) of Windkraft Simonsfeld AG in Ernstbrunn (Lower Austria) is a PEB completed in 2014. As of October 10, 2021, the project is listed on the klimaaktiv website with Gold certification, reaching 965 out of 1000 points. The building design included seven steps to explore innovative options for energy plus buildings. The façade is optimized for passive solar gains and excellent natural lighting in winter and high gains of thermal and photovoltaic energy in summer („100 % energy façade“). IBO- Austrian Institute for Construction and Ecology, a cooperation partner in the project, provides the measured data. It is an example of for a small surface building that achieved energy self-sufficiency.

3.5 ArcheNEO

ArcheNEO is a highly energy efficient and energy autonomous office park in Kitzbühel Oberndorf, Austria. It has been developed as an integrated ecological project from the very beginning. The main target was to produces more energy than needed from local renewable energy sources. PV system on the roof is programed according to the sun calendar. Another PV system is integrated in the south façade an inner courtyard. An integrated energy concept saves energy, uses renewable energies in combination with electric mobility and batteries as electricity storage. The goal was to achieve a building with no need of external energy and no CO_2 emissions. As claimed on the Building of Tomorrow website ArcheNEO serves as a demonstration project and will be multiplied and exported.

3.6 Green Office Meudon

This office building is the first experience of the "Green Office" concept developed by the company Bouygues Immobilier and the first large-scale positive-energy office building in France. The building is located in Meudon la forêt (France) and hosts a computer centre working 24h/24. The dimensions of the building are considerable, and space design was took into account how to facilitate reductions in energy requirements (more than half of the floors are no more than 13.5 m deep). Natural ventilation replaces air conditioning in summer and the building is equipped with a cogeneration unit and 4100m2 of photovoltaics panels. The SI@GO software application measured Green Office® Meudon’s energy production and consumption after a year in operation, so real data are available for analysis on the Green Office website. This is the case study represents the largest office building considered in the study.

3.7 Green Office Rueil

Green Office Rueil is located in Paris and has HQE and BREEAM certifications. Is divided into two separate buildings, and the West building data are available. The building has a linear north facade and a curved south facade that promotes solar gain. The bioclimatic architecture favors natural light and features a rainwater recovery system. The facades on the East and West orientations have been minimized for summer comfort. The data for the West building was calculated according to the French Regulation RT2012 and can be found on the BEPOS Observatory website.

3.8 Arkinova Activity Generator

Arkinova Activity Generator in Anglet is a building for l'Agglomération Côte-Basque-Adour with a mixed program (office, co-working spaces, FabLab), a technology hub dedicated to eco-building, bringing together young start-ups, R&D companies, architects and engineers. It has the double certification NF HQE Tertiary Buildings - New or Renovation and BREEAM. The materials that were used have a low energy and carbon footprint, enabling the structure to be energy positive. Passive design strategies are favored over technical means. Thus, natural ventilation ensures summer comfort; the envelope has an efficient insulation and optimizes solar and luminous gains (Agence Guiraud-Manenc 2017). This building achieved the highest energy-sufficiency ratio among the analyzed case studies.

3.9 Pépinière d'entreprises in Montlieu la Garde

Pépinière d'entreprises in Montlieu la Garde is interesting as case study because currently it is one of two buildings in the Observatoire BBC database that is certified with new Bepos + Effinergie 2017. This building is a business incubator for wood enterprises located in the town of Montlieu la Garde. Its structure is made of solid timber. The data was calculated according to RT 2012 - E+C and conclude that the degree of energy self-sufficiency was achieved with ease.

Moreover, the next NZEBs are analyzed:

3.10 Elithis tower

The Elithis tower was designed to be a PEB, and although it did not reach the positive energy balance, it’s still an example of good energy balance and economic performance and the first zero energy office building in France. The design singularity of being a tall building with a small footprint helps quantify the pros and cons of such design solutions when designing a PEB building that needs to maximize the integrated PV area in the building envelope. After one year of occupancy first energy report was elaborated with data collected by the help of more than 1600 sensors that permit examine and analyze all consumptions. The consumption values were increased because of some factors. It was concluded that the zero energy could only be reached by the users and their behaviour inside (Lenoir, Wurtz, and Garde 2011).

3.11 Pixel Building

The Pixel building is the first office building with none carbon dioxide emissions and is able to generate its own energy and water. It ranked first in the certificate conceded by the Green Building Council in Australia. Therefore, the focus for the Pixel project has been carbon balance rather than energy. A system of perimeter planters, fixed shading louvers and solar panel shading are installed in the façade along with smart window technology for night cooling. Natural light and natural ventilation help to minimize the building energetic requirements (Esmore et al. 2011).

3.12 Zero Building

The Zero Building located in San Sebastian (Northern Spain) is an office building part of the Ideo Campus, that comprises neighborhood four buildings. The Zero building was both LEED and BREEAM certified and is an example of bioclimatic design, and needs no fossil energy, as the heating and cooling comes from a local district facility run by 100% renewable energy sources such as biomass, solar thermal and geothermal energy. Renewable electrical energy is generated through the integrated solar panels on its inclined roof. The roof inclination maximizes the solar gain of the PV and they are able to generate 76,9% of the total annual consumed energy. The real monitoring data have been analyzed and published (Barrutieta et al. 2021).

3.13 UBA 2019

UBA 2019 was designed and built in Berlin (2009-2013) as the first net zero energy building of the German Federal Government. The building only requires electric energy without in-situ combustion of fuels and compensates the energy demand by local conversion of energy from on-site renewable energy resources. The building has a compact square shape. The energy performance is continuously monitored in terms of the energy demand of each use, the on-site energy conversion from renewables, indoor conditions.

During the first year of operation, high differences between measurements and simulation in some energy uses (higher demand for heating, and lower for lighting, office equipment and ventilation) were revealed, the overall electric energy demand is similar to the expected. The reasons for this performance gap are the occupants' behaviour and the patterns of use of the building. Moreover, the measured electricity production from photovoltaics is much higher than designed, so the building is classified not as a "zero" but as a "plus" energy house. The maximization of the self-use of the energy produced on-site by means of suitable storage systems is a further step (Ascione et al. 2016).

Table 2 introduces the case studies and provides general data, as location, use, net floor area and energy self-sufficiency. These data are obtained based on the literature review realized as explained in section 2.1 and the sources are indicated in the column Sources. Further documentation and information for each building was obtained by consultations made to the references given in the papers. The following criteria have been taken to homogenize the collected data in tables 2 and 3:

- Floor net area refers to the area of the building that is climatically conditioned (Net Floor Area column in Table 2).
- Final energy consumption refers to the energy really measured in the buildings in the case of Real measured data (Data type column in Table 3). Translation into Primary Energy has been made using conversion factors at national scale that correspond to the monitored year.
- The primary energy balance refers to the electricity generated annually in the building by its PV systems, in comparison to its consumed primary energy per m2.

Table 2 is complementary to Table 3, where more relevant KPIs are introduced for each selected case study, such as energy generation sources and homogenized energy performance indicators. The self-sufficiency indicator derives from data in Table 3.

Table 2. Selected projects

Project	Category	Type[1]	Location	Climate zone (Open Street Map project)	Year	Net Floor Area	Self-sufficiency in %[2]	Sources
Powerhouse Brattørkaia	PEB	O	Trondheim, Norway	Dfb	2019	14 280	120,7	(Jenssen 2019), Powerhouse website
Freiburg's New City Hall	PEB, *Award Climate Positive 2019*	A	Freiburg, Germany	Dfb	2017	21 819	98,8	(Réhault et al. 2019), (Jaeger et al., n.d.), DGNB website
Aspern IQ	PEB, TQB (Total Quality Building Assessment of the Austrian Sustainable Building Council), *klimaaktiv GOLD*	T	Aspern, Austria	Cfb	2012	7 326	>100	(Weiss, and WA Business & Service Center GmbH 2013), Passivhaus database, Cravezero
Windkraft Simonsfeld AG	PEB, *klimaaktiv GOLD*	O	Ernstbrunn, Austria	Cfb	2014	867	114,4	(Mayer, Reinberg, and Waltjen 2015), (Lechner et al. 2014), (Bintinger, n.d.)
ArcheNEO	PEB	O	Kitzbühel, Austria	Dfb	2017	6 500	108,5	Building of Tomorrow, Archeneo website
Green Office Meudon	*BBC-effinergie*	O	Meudon (Paris), France	Cfb	2011	22 800	114	(Jäger 2020), (Cartier 2012), (Lenoir et al. 2010), (Lenoir, Wurtz and Garde, 2011)
Green Office Rueil (Ouest)	PEB, *Bepos Effinergie 2013, BREEAM Very Good*	O	Rueil Malmaison, France	Cfb	2015	14 997	110,5	Observatoire BBC database, (Cartier 2015)
Arkinova Activity Generator	PEB, *Bepos Effinergie 2013, HQE, BREEAM Pass*	O	Anglet, France	Cfb	2016	1 238	238,3	Observatoire BBC database, (Agence Guiraud-Manenc 2017), (Guiraud and Manenc. 2018)

Pépinière d'entreprises	PEB, *BEPOS+ effinergie 2017 - E4C1*	PO	Montlieu la Garde, France	Cfb	2018	604	170,8	Observatoire BBC database
Elithis tower	NZEB	O	Dijon, France	Cfb	2009	4 567	27,7	(Lenoir et al. 2010), (Lenoir Etienne Wurtz and Garde, 2011) (Leysens 2010), (Perruchot 2019)
Pixel building	NZEB, *LEED Platinum*	O	Melbourne, Australia	Cfb	2010	837	68,3	(Esmore et al. 2011), ("Carbon Neutral Offices- DRAFT > The Pixel Building Case Study SNAPSHOT Organisation Building Type Commercial Offices" n.d.)
The Zero Building	NZEB, *LEED Gold, BREEAM Excellent*	O	San Sebastian, Spain	Cfb	2013	17 505	76,9	(Barrutieta et al. 2021)
UBA 2019	NZEB	A	Berlin, Germany	Dfb	2013	1 178	155,7	(Ascione et al. 2016)

1- O- office; PO- public office; A- administrative; T- technology centre
2- Self-sufficiency = primary energy generation/ primary energy consumption

4. Comparative analysis of the case studies

The aim of the research is to identify the main tendencies in current NZEB and PEB designs and to assess their real impact to reduce CO_2 emissions and to achieve effective energy self-sufficiency. Firstly, a comparative chart with homogenized energy data has been elaborated. Secondly, the most significant renewable and sustainable energy solutions have been identified with a specific focus on PV solutions and their relevance towards achieving energy self-sufficiency without the use of fossil fuels. Finally, a relevant ratio for the architectural design of PEB buildings is proposed, and it is calculated for the analyzed case studies: the relation between PV area and net floor building area.

4.1 Renewable energy generation sources and energy consumption data

Energy data parameters, commonly used to describe this type of buildings, have been gathered to be illustrated in a common case study chart. In order to achieve a consistent comparison with the energy data of the analyzed case study buildings, a necessary homogenization task has been carried out. This process has consisted in a revision of the data found in the mentioned sources. It has been verified if they refer either to the final energy or the primary energy data, and the conversion factor available for each country has been applied.

For the Zero Building, for example, the measured energy corresponds to the real end-use energy (or final) consumption in the building during a whole year of operation. This energy was transformed into Primary Energy figures by the application of weighting factors. These factors are published by the Ministry for the Ecological Transition and the Demographic Challenge (MITECO) (Ministerio de Industria 2016).

As explained before, most of the cases' available measured and verified performance data is found in primary energy and for time span of one year. Heating, cooling and electricity energy consumption, as well as renewable energy generation based on monitored or simulated data is expressed in a numeric indicator of primary energy use in kWh/m2.yr. The primary energy considers the difference in generation and distribution by different energy carriers. For decarbonization goals, savings in primary energy are more important than savings in final energy.

The found simulated results are expressed in primary energy and for time span of one year. The data for the cases located in France is calculated according to RT 2012 - E+C. Pixel building's energy performance was modeled using the building energy simulation tool Indoor Climate and Energy.

Table 3 addresses the renewable energy generation sources and primary energy consumption.

Table 3. Energy data

Project	Data type[1]	RE generation sources[2]				Final energy consumption	Primary energy generation	Primary energy heating	Primary energy cooling	Primary energy electricity	Total primary energy
		PV	ST	HP	CHP	kWh/m2.yr					
Powerhouse Brattørkaia	R+S	•		S		-	33,70	4,40	0	22,70	27,90
Freiburg New City Hall	R	•	•	G	x	25,08	63,50	17,10	0,90	46,30	64,30
Aspern IQ	R+S	•		G		-	-	21,60	7,36	-	-
Windkraft Simonsfeld AG	R+S	•	•	G		43,30	127	4,20	0	91,20	111
ArcheNEO	S	•		G		13,61	34,90	-	-	-	34,90
Green Office Meudon	R	•			•	62	101	33,80	1,6	37,40	88,56
Green Office Rueil (Ouest)	R+S	•		G		24,00	57	11,50	7,40	27,40	46,30
Arkinova Activity Generator	S	•		A		17,09	105,10	16,50	0	19,60	44,10
Pépinière d'entreprises	S	•		A	•	25,85	125,40	38,50	4,60	23,60	66,70
Elithis tower	R	•			•	11	18	11	10	35,5	65
Pixel building	S	•			x	68,70	84	8,4	75,20	39,40	123
The Zero Building	R	•	•	G	•	21,03	15,62	3,80	3,87	12,65	20,31
UBA 2019	R	•	•	G		41,22	150,60	21,85	10,26	69,50	96,70

1- R- real, S- simulated
2- PV- photovoltaic, ST- solar thermal, HP- heat pump (G- ground, A-air, S- seawater source), CHP- cogeneration heating plant (•- on biomass, x- on gas)

4.2 Energy generation sources and sustainable solutions

All of the buildings use photovoltaic systems for on-site energy generation. Heat pumps are the second most used energy generation source (in ten buildings), followed by CHP (4 biomass and 2 gas fuel), finally, four of the fourteen cases integrate solar thermal system. In addition, Pixel Building and Aspern IQ Technology Centre use small wind turbines, although the wind-produced energy is considerably less than PV.

All of the PEBs except Green Office Meudon use heat pumps; mostly ground source, one seawater-sourced (Powerhouse Brattørkaia), Pépinière d'entreprises and Arkinova have air source heat pumps. As for the NZEBs, only two have heat pumps (The Zero Building and UBA Office), both ground source. Moreover, free cooling from ground source heat pumps are used.

Only three of the PEBs have a secondary renewable generation source to support the heat pump and to cover peak loads when PV generation is not sufficient to cover consumption (rapeseed oil in Meudon, wood in Pépinière d'entreprises and gas in Freiburg City Hall). In the same time, three out of four NZEBs have CHP: two work on biomass (pellets) and one on gas (Pixel building).

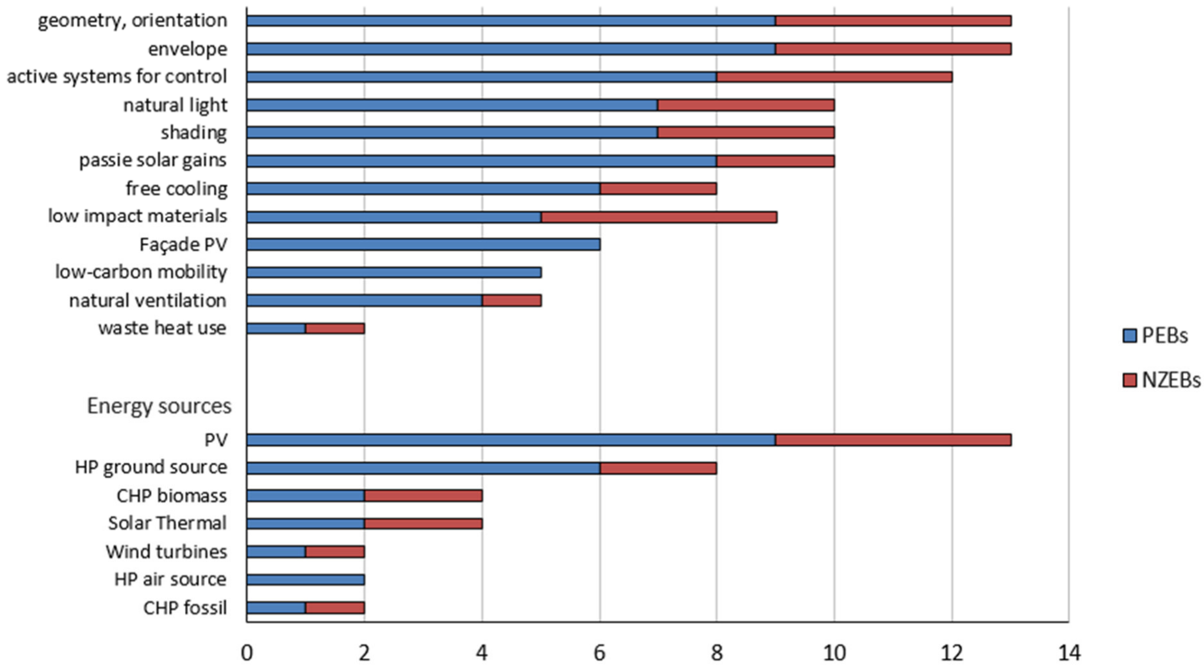

Figure 1. Buildings' sustainable and renewable energy solutions

In total, the selected buildings use 19 different sustainable solutions. There are eight types of energy generation sources: photovoltaic, solar thermal, heat pumps with ground (one seawater) and air and sources, wind turbines and CHP on biomass. However, two buildings use CHP on gas. Regarding passive design strategies, the most used are compact building shape and orientation (applied in all the buildings), natural lighting, shading, passive solar gains and five buildings have natural ventilation. All the buildings have an optimized envelope. Moreover, they use active systems for indoor comfort control and management, free cooling from ground source heat pumps and reuse waste heat. Six PEBs have PV systems installed in façade in addition to roof, while NZEBs do not use this solution. Five PEBs have provisions for low carbon mobility (electric car or bicycle powering systems). Nine buildings use low environmental impact construction materials.

Both PEBs and NZEBs use active systems for indoor comfort control and management and monitor it after the building is delivered. In some cases, user satisfaction poll is made (Windkraft Simonsfeld AG and Aspern IQ Technology Centre). In the Elithis tower, for example, a notice board located in the entrance of the building displays the daily energy consumptions and the savings realized (in kWh and tons of CO_2) in order to sensitize the users. Designed with the aim of evaluating, understanding and modelling the impact of the users' behavior the building is the opportunity to test new sensitization systems not only in terms of energy savings, but also low-emission transports, paper or water savings, waste sorting (Lenoir, Wurtz and Garde, 2011).

The buildings have different primary energy balance. As shown in the table below, most of the buildings positioned as PEBs generate more than 8% of energy surplus from photovoltaics on annual balance. In particular, nine of ten PEBs produce more renewable energy than consume for their operation on an annual basis (between 108,5 and 272,7 % of the consumed primary energy). It should be taken into account that for four of the PEBs only simulation energy data are analyzed. NZEBs compensate between 27,7 and 155,7% of the consumed primary energy. However, self-consumption of the generated energy was not considered.

One of the four analysed NZEBs have positive primary energy balance. UBA Office can be classified as a "plus" energy building because the electricity production from photovoltaics was much higher than designed.

As for the Elithis tower, ten years after its operation the engineering company Elithis presented a report with monitoring results. Probably, a bigger PV area or modern technologies would help the tower to achieve the positive energy balance (Perruchot 2019).

In case of the Zero Building, if the supplied grid energy is replaced with a 100% green and renewable energy as proposed (Barrutieta et al. 2021), the consumption of primary energy will be also reduced and by the increase of PV energy generation, positive energy balance could be probably achieved.

4.3 Photovoltaic energy generation and primary energy balance

In the following table, photovoltaic surface in the building and its energy generation data are compared. The primary energy balance refers to the electricity generated in the building by its PV systems, in comparison to its consumed primary energy per m^2.

The available data for the global solar irradiance parameter were obtained from the Energy Plus weather database. The data is available for the capitals of regions, so the data for the following cities was chosen: Vienna, Innsbruck, Berlin, Stuttgart, Bordeaux, Paris, Dijon, Melbourne and San Sebastian. As for Norway, only Bergen and Oslo data is available, so although the analysed building is located in Trondheim, Bergen data was considered.

Table 4. PV comparison

Project	**GHI[1]**	**PV system[2]**	**Data type**	**PV generation**	**PV generation / m^2**	**Peak power**	**Installed PV roof area**	**Installed PV façade area**	**PV area to net floor area ratio**	**Primary energy balance**	**Produced/ consumed**
	kWh/ m^2/yr.			kWh/yr	kWh/yr.m^2	kWp	m^2	m^2	%	kWh/yr. m^2	%
Powerhouse Brattørkaia	746,75	R+ F	R+S	481 000	33	576,9	1886	981	20	5,8	120,7
Freiburg New City Hall	1093,45	R+F	R	554 100	63,50	682	-	1848	8	-0,8	98,8
Aspern IQ	1122,44	R+F	R+S	-	50,40	144,8	1300	total	14	-	100
Windkraft Simonsfeld AG	1122,44	R+F	R+S	55 046	63,50	47	242	137	44	16	114,4
ArcheNEO	1145,53	R+F	S	226 750	35	94,8	1300	-	20	2,7	108,5
Green Office Meudon	1068,14	R+F	R	427 850	19,90	600	2100	2100	20	12,4	114
Green Office Rueil (Ouest)	1068,14	R	R+S	-	57	362,9	1715	0	11	5,4	110,5
Arkinova Activity Generator	1264,57	R	S	-	105,10	558	190	0	15	61	238,3
Pépinière d'entreprises	1264,57	R	S	-	125,40	29,10	161	0	27	52	170,8
Elithis tower	1177,95	R	R	185 760	40,67	-	456	0	10	-11	27,7
Pixel building	1583,23	R	S	6 665	8	6,3	38,4	0	5	-39	68,3
The Zero Building	1171,19	R	R	273 380	15,62	230	1291	0	7	-4,7	76,9
UBA 2019	985,48	R	R	177 351	150,55	66,3	391	0	33	53,9	155,7

1- Global Horizontal Irradiation (GHI): Long-term yearly average of yearly totals measured in kWh/m^2/yr.

2- R- roof, F- façade

3- R- real, S- simulated

It is assumed and checked that the PV panel performance is coherent to a mean monocrystalline panel performance. The performance of the PV façade is usually lower than in the roof, but it results in a necessary contribution to achieve PEB standards in buildings that are not especially designed with a low rise shape. The need to introduce a PV façade to achieve the PEB standard is a fact of interest that is relevant in the early design stages and could be further researched.

Six out of thirteen buildings have PV systems installed on the façade in addition to the roof. For three of them PV façade and roof area data is available (Powerhouse Brattørkaia, Windkraft Simonsfeld AG, Green Office Meudon). It is interesting to note that the relation of PV system installed on the façade to PV system on the roof is from 50 to 57 %.

As for the photovoltaic generation, Pépinière d'entreprises and Arkinova Activity Generator have the highest values- more than 100 kWh/yr.m^2 (the three buildings have only simulated data). The rest of the PEBs produce from 33 to 63,5 kWh/yr.m^2. Among NZEBs, the generation varies from 8 to 41 kWh/yr.m^2, except UBA Office building that generates 150,55 kWh/yr.m^2.

4.4 Relation between PV area and net floor building area

First of the proposed ratios is the relation between PV area and net floor building area. On the early design stage, this ratio helps predict in the project the PV area needed according to the building's scale. This would sum both roof and façade PV systems, taking into account a mean monocrystalline panel performance. Thus, the photovoltaic system could be well integrated in the design of the building from the beginning.

Most of the buildings' PV systems have area equal to 10-20% of total building's net floor area. Medium ratio is 18%, 19% for PEBs and 14% for NZEBs. The PEBs that are on the extreme of this 10-20% range (Freiburg City Hall -8%, Pépinière d'entreprises -27%, UBA Office -33%, and Windkraft Simonsfeld AG -44%) are very big or very small-scale buildings. In general, small sized positive energy buildings have a higher ratio (more than 20%), except the Arkinova Activity Generator building with 15% ratio. Meanwhile, small and medium sized NZEBs ratios are less than 10%, except the UBA Office that has a ratio of 33% but it can be considered a PEB because of its positive annual balance (Ascione et al. 2016). Large and medium PEBs and NZEBs have ratios around 10-20%.

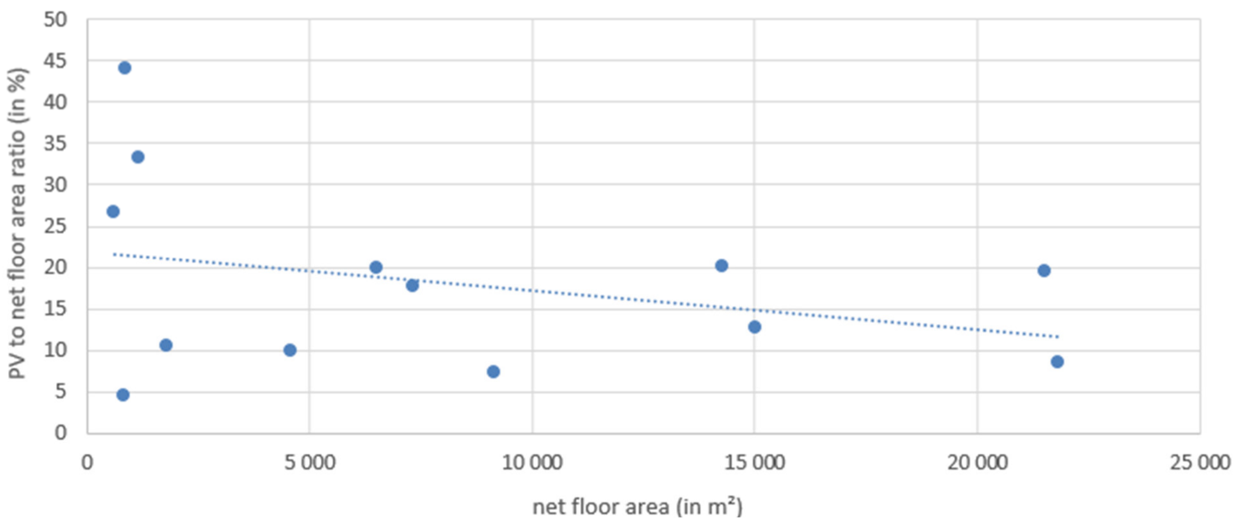

Figure 2. Relation of the PV area ratio to the size of the building

Large building in dense urban zones require compact building shapes that enable optimizing land area use, but have low roof area to envelope area ratio. Therefore, for large buildings like Freiburg City Hall and Powerhouse Brattørkaia, photovoltaic system on the façade, despite of its low contribution to the total solar gain (approx. 18% in Freiburg and approx. 22% in Brattørkaia), is decisive for reaching a plus energy balance. Small area buildings with positive annual balance (Windkraft Simonsfeld AG, Pépinière d'entreprises and UBA Office) have the highest ratios: 44, 27, and 33% respectively.

In conclusion, eight of nine PEBs produce more renewable energy than consume for their operation on an annual basis (between 108,5 and 272,7 % of the consumed primary energy). It should be taken into account that for four of the PEBs only simulation energy data are analyzed. NZEBs generate between 27,7 and 155,7% of the consumed primary energy.

Freiburg City Hall almost reached plus energy balance. In winter, the building mainly consumes power from the grid. Besides, there are some flaws in BIPV and heat and cold generation systems, as well as use of fossil gas. Currently, the city of Freiburg is implementing corrective measures (Réhault et al. 2019).

In terms of potential upgrade of NZEBs to PEBs, the following recommendations could be given. In general, there are two ways to improve the primary energy balance: to increase the PV energy generation or to decrease the consumption with more efficient systems, or by more energy efficient user behavior. Therefore, a bigger PV area or modern efficient technologies, probably, would help to achieve the positive energy balance. User sensitization systems would also be helpful. The occupants play a role in reducing the gap between real building performance and expected behaviour and could be involved in a synergy among design, management and use of buildings. The sensitization of the users is essential in this type of building. The aim is to build passive rather than active buildings, with active rather than passive occupants (Lenoir, Wurtz and Garde, 2011).

4.5 Relation between PV to area ratio and self-sufficiency

It results interesting to relate the obtained PV to area ratio with self-sufficiency. As can be noticed from the figure bellow, higher PV to area ratio corresponds to higher self-sufficiency. An exception can be

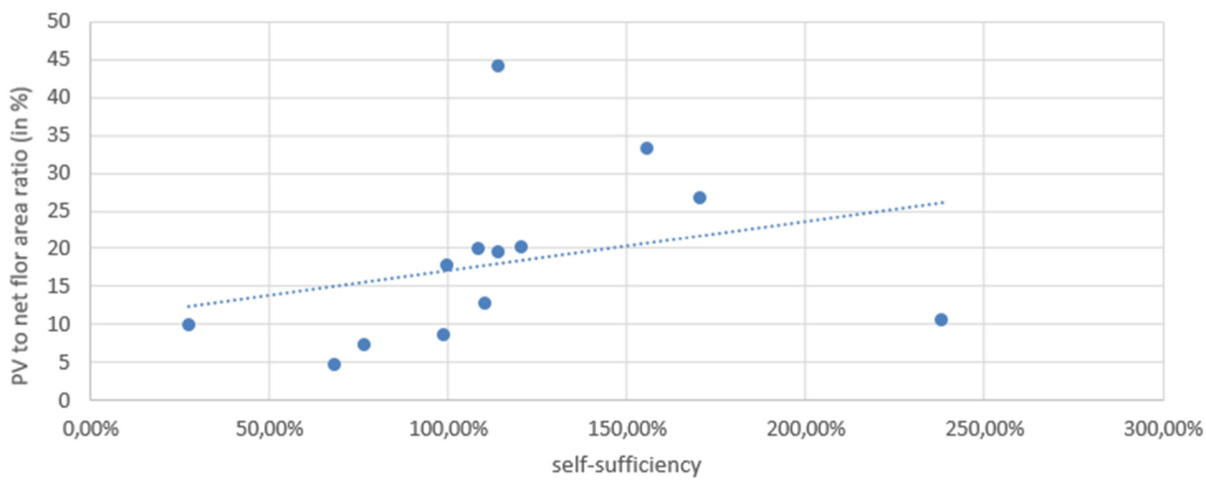

Figure 3. Relation of the PV area ratio to self-sufficiency (in %)

Arkinova Activity Generator that has 238 % of self-sufficiency and PV ratio of 10 %, but as mentioned above, only simulated data is available for this building.

Most of the buildings have self-sufficiency ratio from 100 to 150% have PV to area ratio from 13 to 20%. However, high PV area ratio does not always guarantee high self-sufficiency. For instance, Windkraft Simonsfeld AG has ratio of 44% and self-sufficiency of 114%. For the analyzed case study buildings with self-sufficiency lower than 100% (negative energy balance) the PV to area ratio ranges from 5 to 10%.

The exceptions to the trends of some the building case studies are interesting to be further studied. The self-sufficiency ratio may be conditioned to some extent by architectural design factors such as the form factor given to the buildings, the height of them vs. the floor area ratio and the compacity of the building shape.

4.6 Relation between PV area ratio and global horizontal irradiation

As explained previously, global horizontal irradiation (GHI) provides a simplified approximation to the potential for PV power production and allows comparison of the available natural conditions without considering a particular technical design and mode of operation.

In the following figure, the relation between solar radiation and the PV area ratio is shown.

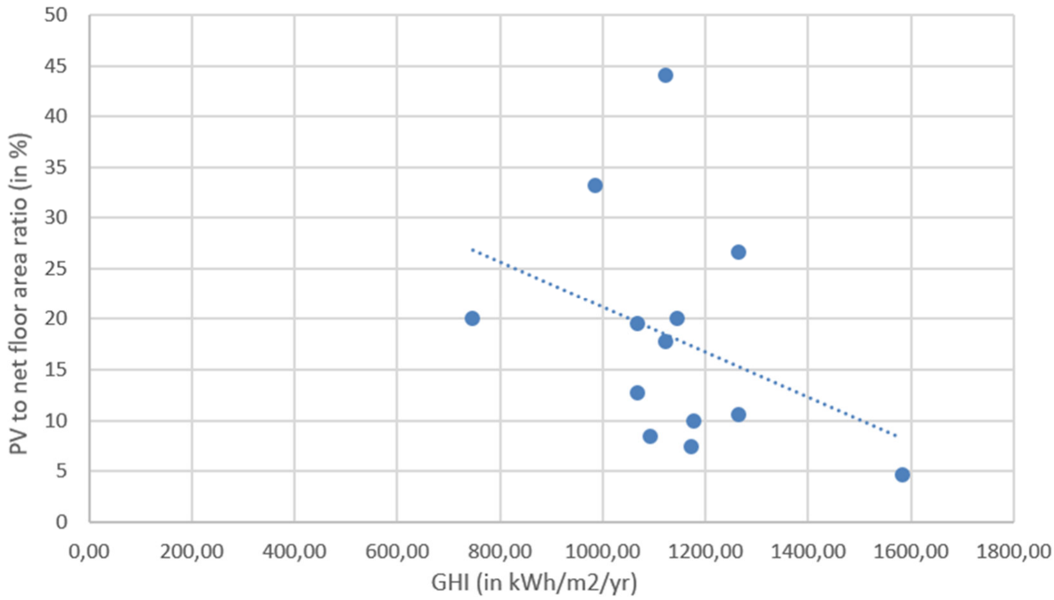

Figure 4. Relation of the PV area ratio to GHI (in kWh/m²/yr.)

Eight of the buildings are located in sites with GHI from 1068,14 to 1177,95 kWh/m²/yr. In addition, there are two buildings in the Bordeaux region with GHI of 1264,57 kWh/m²/yr. and one in Berlin (985,48 kWh/m²/yr.). The highest GHI is in Melbourne (1583,23 kWh/m²/yr.) and the lowest is in Norway (data for Bergen, 746,75 kWh/m²/yr.).

The trend line shows that buildings located in sites with higher GHI have lower PV area ratio. For instance, among the eight buildings with GHI yearly totals around 1000-1200 kWh/m², the three with the lowest PV area ratio (lower or equal to 10%) do not achieve positive energy balance. The rest of the buildings within the same GHI values have higher PV ratios (minimum 13% and maximum 44%) and positive energy balance. The UBA building located in Berlin has PV ratio 33% (real monitored data available). As for the Bordeaux region cases, Arkinova Activity Generator and Pépinière d'entreprises have PV ratio of 11 and 27% respectively, both with positive energy balance but with only simulated data available. Powerhouse building located in the site with less solar irradiation has ratio of 20% and achieves positive energy balance, while Pixel building located in Melbourne with highest GHI has PV ratio of 5% and is not self-sufficient. This results can be attributed to the geometry and size of the buildings (Pixel building is a small-scale building and Powerhouse Brattørkaia a medium one). Moreover, the results also show that the PV ratio of 20% or more is valid for all the studied sites.

5. Conclusions

According to the general definition, a building is considered plus energy if during its lifecycle it produces more energy from renewable energy sources over the course of a year than it needs for operation. It is possible to include also the energy embodied in materials construction and demolition. The PEB concept focuses on a holistic approach to high-energy performance rather than on a simple generation and export of the excess energy.

This paper analyses several PEB projects from different databases with real monitored data and links them with selected NZEB cases discussing their potential of achieving positive energy balance.

The selected cases are examples of the actual PEB concept's implementation in the context of office buildings in some European countries. In summary, eight out of nine selected PEB cases produce more renewable energy on site than consume on annual basis. All of the buildings use photovoltaic systems for on-site energy generation. Heat pumps are the second most used energy generation source followed by CHP (biomass and gas fuel); finally, four of the fourteen cases integrate solar thermal system. Other energy generation sources are small wind turbines, although the wind-produced energy is considerably less than PV. All of the PEBs except one use heat pumps, mostly ground source, air source heat pumps and one seawater-sourced. As for the NZEBs, two have heat pumps, both ground source. Moreover, free cooling from ground source heat pumps is used.

The research focuses on photovoltaic system in the selected projects and the achieved degree of electricity self-sufficiency. First of the proposed ratios is the relation between PV area and net floor building area. This approximation would be useful for planning photovoltaics integration solutions from the early architectural design stage. An optimum solution for a medium-sized positive energy office building is to provide for the PV system the area equal to at least 10-20% of the total building area.

According to self-sufficiency ratio, the buildings that have PV to area ratio from 13 to 20% are self-sufficient from 100 to 150%. For larger buildings, a smaller ratio is possible. In cases that PV to area ratio ranges from 5 to 10% the self-sufficiency lower than 100% (negative energy balance). Moreover, the PV installation in the façades results decisive for reaching positive energy balance, especially for large compact buildings with a low roof to envelope area ratio. The relation of the PV system installed on the façade to PV system on the roof is from 50 to 57 % for the studied buildings.

As for the natural conditions impact on the PV ratio, site solar radiation has been considered. The Global Horizontal Irradiation (GHI) variable was addressed for each case study. Buildings located in sites with higher GHI tend to have a lower PV area ratio. Within the same GHI range, buildings with a higher PV area ratio achieve positive energy balance. For instance, in sites with GHI ranging from 1000 to 1200 $kWh/m^2/yr$. buildings with a PV area ratio lower than 10% are not self-sufficient, while the PV ratio of 20% or more is valid for all the studied sites.

The research provides an approach to PV integration from the early stages of the architectural design of a building to ensure a satisfying energy self-sufficiency performance and a better aesthetic, constructive and economic integration of PV in the architectural design. Further research will be conducted introducing new factors related to early architectural design decisions, namely the shape of the buildings, and their height. Furthermore, the relation between the PV ratio and roof to envelope ratio or building geometry (compactness) could be analyzed as an indicator to potential self-sufficient design.

The findings of this research method and the rations between analyzed indicators could be applied to other typologies such as educational buildings and dwellings where demands and consumptions patterns differ.

Therefore, this study could be a relevant contribution for further development of a solar design approach that will be reshaping the cities and architecture to address the global climate crisis and the reduction of fossil fuel consumption.

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