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Decision-making framework for positive energy building design through key performance indicators relating geometry, localization, energy and PV system integration

X. Barrutieta [a,b,*,1], A. Kolbasnikova [b], 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

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ABSTRACT

The effectiveness of positive energy building (PEB) design largely depends on a balanced approach between building design and energy performance. The current common architectural process is lacking guidelines to address the impact of early design decisions in achieving the energy positive building goals. A selection of case study office buildings with an intended architectural diversity provide homogenized real data for this research.

The aim is to find connections among four fields that are relevant for the PEB design process: building geometry, location, energy consumption and building integrated photovoltaics. The interrelations among them are synthesized in several novel key performance indicators (KPIs) that conclude, i.a., that only buildings with a roof-to-façade area ratio higher than 28% may achieve a 100% self-sufficiency. The PV area corresponding to 15% of the envelope is a necessary starting threshold to achieve a self-sufficient PEB. The installed power capacity of the PV system should be above 30 Wp/m2c.

The main contribution is a decision-making framework that can be sequentially applied providing useful limits, thresholds and figures that guide towards effective architectural decisions for PV system integration in the early PEB design process.

1. Introduction

1.1. PEB state of the art and the relevance of BIPV to achieve energy self-sufficiency

The European Union set a goal of developing a sustainable, competitive, safe and decarbonized energy system by 2050. In the building sector, the EU has established a legislative framework that includes the Energy Performance of Buildings Directive EU (EPBD, 2018/844/EU) [1] and the Energy Efficiency Directive (EED, 2018/2002/EU) [2] in response to the goals of decarbonization and energy consumption minimization and to improve the energy performance of buildings. Both directives were amended as part of the "Clean Energy for all Europeans" package and came into force in 2018 and 2019. According to these directives, member states had to ensure that by 31 December 2020 all new buildings are nearly zero energy and cover the energy demand to a very significant extent by energy from renewable sources, including energy from renewable sources produced on site or nearby. This has promoted the implementation of on-site renewable energy generation in the building sector, mostly PV, and has increased the interest in optimizing PV systems, improving their design, performance and integration. In 2021, about 28.6% of the world's electricity was generated by renewable sources, 13.3% of which is solar [3]. Among all the renewable resources, solar energy is the most abundant, inexhaustible and the cleanest [4]. Additional solar-accessible areas (such as external facades) are needed to provide the necessary electricity for building applications. Solar roofs are now evolving into a complete active building skin and PVs have become part of the aesthetics of this technology [5].

Nowadays, NZEBs are already integrated in European building

* Corresponding author at: 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.
E-mail address: xabier.barrutieta@ehu.eus (X. Barrutieta).
URL: https://www.barruarkitektura.com (X. Barrutieta).
[1] ORCID: ResearcherID: P-9258-2016.

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Nomenclature

PEB	positive energy building
PED	positive energy district
NZEB	net zero energy building
BIPV	building integrated photovoltaics
BAPV	building applied photovoltaics
KPI	key performance indicator
GHI	global horizontal irradiation
HEI	height index
Ess	energy self-sufficiency
Egen	energy generation
Eco	energy consumption

regulations and the next level of certification for highly efficient sustainable buildings is being introduced. Positive energy buildings (PEBs) produce more energy from renewable energy sources over the course of a year than they need for heating, cooling, ventilation, domestic hot water (DHW) and auxiliary systems [6]. A literature review was conducted to assess the definition of the PEB concept. A range of publications consider the state of the art of PEBs, or assess PEBs as the evolution of NZEBs [6–10]. The literature review showed that despite its rising popularity, the PEB concept still has no universal definition, focusing on a holistic approach to high energy performance rather than on a simple generation and export of the excess energy. Several PEB standards were developed to define the main criteria for PEB, such as the energy balance contributions, physical boundary, the time span of evaluation, the metrics of evaluation and added value in sustainability and indoor comfort [11]. Some of the definitions are promoted by governmental institutions or are EU funded (EXCESS definition, BEPOS + effinergie 2017 (E4 C1/C2) in France, Efficiency House Plus in Germany), while others are developed by private company initiatives like the Powerhouse standard. A wide range of European programmes promote the implementation of PEBs and positive energy districts (PEDs). To state some, the Program on Positive Energy Districts and Neighborhoods (PED Program) established in 2018 [12] and IEA EBC Annex 83 [13].

The PEB definition proposed by EXCESS includes all of the above-mentioned criteria and defines a PEB as an energy efficient building that produces more energy than it uses via renewable sources, with a high self-consumption rate and high energy flexibility over a time span of one year. It is valid for all new and retrofit buildings and takes into account the energy and environmental performance of the building, economic evaluation, social and technological perspectives [14].

The growing interest in on-site energy generation has led to the development of numerous research studies on the theme of PV in PEBs ([15]). Many of these analyse the topic of how the system is integrated [16], address criteria for architectural integration of the PV [17], introduce a method for the optimization of the envelope for the best building integrated photovoltaics (BIPV) placement based on the shape grammar including architectural preferences [18], or address the functionality of PV in fenestrations. Mandalaki, Tsoutsos, and Papamanolis assess different typologies of BIPV shading systems using computer simulations and physical models in terms of energy savings and the quality of the visual interior environment [19].

Several research studies address the optimization of PV systems according to the orientation and the number of the PV panels, as well as their inclination and direction ([20;21]). Skandalos [22] proposes a BIPV design framework for adaptation to local climate and maximization of energy generation in four climate zones according to the amount of horizontal irradiation. Other papers assess the minimization of the mismatch between the generated power and the loads ([23,24]).

Photovoltaics integrated in the building envelope, such as the roof or the façade, are referred to as BIPV. Photovoltaic modules are considered to be building-integrated if they have been designed following the basic requirements for construction works in order to form and/or replace a construction product [25]. In response to the rising popularity of BIPV, the EU's member states have developed legislative support schemes [26].

The topic of BIPV has also been addressed by several researches ([27–29]) that review the state of the art in BIPV technology, the PV elements and construction materials advertised as BIPV-products and façade integrated photovoltaics respectively. One paper addresses the current trends in photovoltaic power production and the potential of BIPV for the Agder region in Norway [30]. Kuhn provides an overview of the technologies for BIPV, as well as design options for the integration of BIPV modules in the building envelope [25]. Other researchers assess the main energy-related features of building-integrated photovoltaic (BIPV) modules and systems, such as thermal, solar, optical and electrical aspects [31]. Corti assesses a real case study with monitored data, addressing retrofit scenarios to make building skins active. The aim is to identify the energetic and economic effectiveness of BIPV design options and the correlation between building skin construction strategies and energy and cost parameters [5]. Finally, one study assesses the influence of the angle of the solar cell panel, the albedo of the Earth, the building azimuth and solar cell panels in a model simulation [32].

However, despite the rising number of studies on PEBs and solutions for different climate zones ([33–39]) the literature review showed that there is still a lack of studies comparing PEB solutions in general and BIPV in particular, based on the same climate and assessing case studies with real monitored data. A lack was detected of methodology providing a holistic assessment of BIPV, especially at the urban scale. BIPV affects every aspect of the building design process, therefore a holistic approach is essential for its successful implementation. A comprehensive integrated evaluation system combining architectural design, energy parameters and solar generation technologies is required. This is especially relevant in the context of a holistic approach of PEBs to sustainability and energy efficiency. A holistic bioclimatic integration of PV based on local climate and environmental conditions is crucial in BIPV implementation and needs to be adapted at the early design phase [22]. The role of architects and planners is crucial in the process. Therefore, this paper aims to elaborate a novel design decision-making methodology applicable to the practitioner's field at early building design stages.

1.2. Structure and aim of the study

The main strategy to achieve NZEB and PEB status is to optimize the design and energy efficiency of a building by improving, for example, the geometry and thermal insulation of its envelope. Moreover, the energy demand has to be reduced and the renewable energy production increased [33]. This paper is a continuation of the previous research on PEB concept [40]. The previous paper addressed concept definition, used building solutions and sustainable strategies and discovered that PV system is of outmost importance in this type of buildings. All of the analysed buildings integrate PV systems to generate energy on site. The integration of a PV system clearly contributes to achieving a positive energy balance. For instance, according to research, BIPV can reduce the primary energy balance in office buildings by 25%, while BAPV leads to reduction of up to 33% [41].

The aim of this study is to establish a decision-making tool for PV system design in PEB́s that takes into account a range of factors related to building geometry, location, on site energy generation to meet buildinǵs energy demand and photovoltaic integration. The outcomes of the study and the proposed methodology will provide a practical insight for architects to identify design strategies towards energy self-sufficiency in building design. The main methods used in this research are data processing, ratio and KPI identification, graphics and trends analysis, as well as the proposal of KPIs. For this purpose, the most relevant KPIs that connect design, energy and localization parameters are identified. Therefore, the research is applicable to the practitioner's field in form of a design framework that could be useful for architects from early building design stages to integrate photovoltaic systems into projects and help to design efficient and self-sufficient PEB buildings.

The first chapter contains a short introduction addressing the review of studies on BIPV, research gaps and the aim and novelty of the present paper. In the second chapter, the methodology and the case selection criteria are described in a series of stages from A to G as shown in Table 0. The third chapter presents a summary of data from case studies in Tables 1, 2 and 3. To obtain each buildings geometry data, the buildings were modelled in 3D using the architectural plans. The fourth chapter identifies a set of basic ratios and KPIs drawn from the previous parameters. Their impact and relevancy in the PEB design process is critically discussed. Firstly, relevant basic ratios were identified (Table 4). Secondly, the graphics are presented in order to visualize the existing trends and to propose relevant KPIs. The graphics were studied and several regularities and interesting relations between ratios were found. The results are outlined in the fifth chapter in the form of a design strategy for PEB. Lastly, the sixth chapter presents conclusions and paths for further research.

2. Methodology

The methodology has been ordered in a sequence of phases from A to G, as described in this section. The Table 0 shows these phases along with the keywords.

A) PEB concept and climate

One of the most advanced and relevant concepts for sustainable and low carbon buildings worldwide is positive energy buildings, which can have a relevant impact in for climate change mitigation.

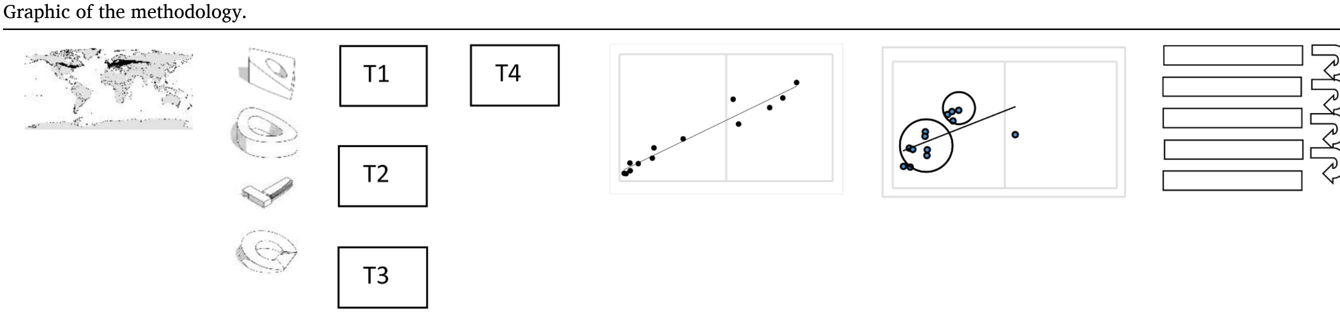
Climatic variation is a key factor in analysing the performance of NZEB and PEB buildings ([33,34,37–39]). This research focuses on a specific climate zone that includes two climate types classified as Cfb and Dfb within the Köppen-Geiger scheme [42,43]. The reason for focusing on these climate zones is that they cover most of Central and Western Europe, where the PEB concept is being developed and where significant clusters of PEB can be found, in particular in countries such as France and Germany [44], including several interesting case studies. Cfb refers to a temperate oceanic climate where the coldest month averages above 0 °C (32 °F) (or −3 °C (27 °F)), and all months present average temperatures below 22 °C (71.6 °F), and at least four months averages above 10 °C (50 °F). Dfb refers to a warm-summer humid continental climate, with the coldest month averaging below 0 °C (32 °F) (or −3 °C (27 °F)), all months with average temperatures below 22 °C (71.6 °F), and at least four months averaging above 10 °C (50 °F). In both climate zones, there is no significant precipitation difference between seasons.

B) Case Studies and selection criteria

The scope of the study focuses on highly efficient exemplary buildings with available energy data, preferably measured and that are located in the mentioned climate zones. The case studies are selected due to their interest as NZEB and PEB buildings, and considering that measured energy and photovoltaic generation data from reliable sources is available. The variability in terms of size, shape, height, etc. is intended to allow visualization of the impact of these design factors in the graphics, and provides a richer scope for the conclusions. However, due to the novelty of the PEB concept and the consequent lack of monitored energy data, the case study selection had to include several exemplary NZEBs with the available measured data. NZEB have the potential to become PEBs [7] and, for the purpose of the research, can be contrasted with case studies that do achieve positive energy balance. The study focused on private and public administration office buildings, one of the reasons being that this particular typology is especially relevant for the research into PV systems. The electricity consumption of office buildings and non-residential buildings in general is very high during daytime, matching the maximum PV electricity generation. Therefore, the self-consumption of the produced energy is high. Moreover, due to high electricity demand in office buildings (lighting, electric appliances), the building optimization is highly important, so office buildings are the most common PEB type and more potential case studies with measured energy data can be found [44].

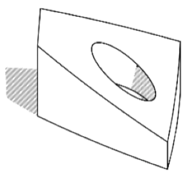
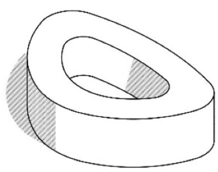
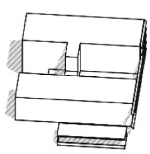
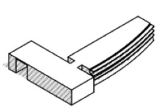
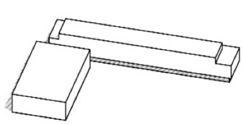
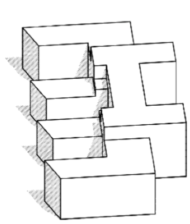
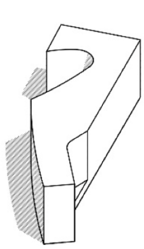
The following criteria were established to select thirteen buildings: new office buildings with a net zero or positive energy balance with available measured and/or calculated energy data located in Cfb/ Dfb climate zone and with PV energy generation. An exception was made for Powerhouse Brattørkaia located in Trondheim due to its high interest in the field of PV integration and positive energy balance. The Köppen-Geiger climate type for Trondheim is oceanic, but closely borders continental, subpolar and subarctic climates [45]. All the selected buildings use photovoltaic systems installed on the roof and six have PV integrated in the façade for on-site energy generation. The net floor areas range from 800 to 21.500 m^2. A certain diversity has also been sought among the selected case studies. The variability in terms of size, shape, height, etc. allows visualizing the impact of these design factors in the graphics, and provides a richer scope for the conclusions. Some buildings are regarded as PEB, whereas real data may contradict this achievement, as well as one of the NZEBs produces more of the energy than it needs to function. This is also part of the findings of the research.

Table 0
Graphic of the methodology.



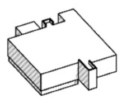
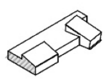
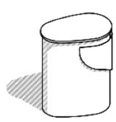
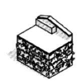
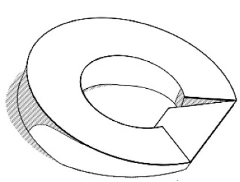
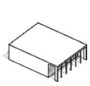
A	B	C	D	E	F	G
PEB REGION CLIMATE	**CASE STUDY** typology real data diversity reliability	**OBTAINED DATA BY FIELD:** location geometry energy PV system	**BASIC RATIOS** numerical values	**KPIs (RELATIONS BETWEEN FIELDS)** in form of graphics	**ANALYSIS AND DISCUSSION**	**DECISION MAKING FRAMEWORK AND CONCLUSIONS**

Table 1
Case study description, location and geometry data.

3D model [1]	Case study data and location	Geometrical data					
	**Year, location, coordinates, latitude (DD), climate zone, PEB/NZEB, awards/certifications, data sources**	**Net floor area** m^2	**Building footprint** m^2	**Roof area** m^2	**Façade area** m^2	**Envelope area[2]** m^2	**Volume** m^3
	**1. Powerhouse Brattørkaia** 2019, Trondheim, Norway 63°25′49.8″, lat. 63.43; * PEB, office [57]	14 280	2 433	2 174	6 860	9 033	55 790
	**2. Freiburg's New City Hall** 2017, Freiburg, Germany 47°59′45″, lat. 47.998; Cfb PEB, administrative Climate Positive 2019 [58,59]	21 819	4 491	3 159	9 980	13 140	76 609
	**3. Aspern IQ** 2012, Aspern, Austria 48° 13′ 2.4″, lat. 48.22; Cfb PEB, technology centre TQB, klimaaktiv GOLD [60,61]	7 326	2 535	2 299	4 387	6 685	29 903
	**4. Windkraft Simonsfeld AG** 2014, Ernstbrunn, Austria 48°31′33.6″, lat. 48.53; Cfb PEB, office klimaaktiv GOLD [62,63,61]	867	562	1 034	1 866	2 899	4 883
	**5. ArcheNEO** 2017, Kitzbühel, Austria 47° 30′ 0.00″, lat. 47.45; Dfb PEB, office [64]	6 500	2 126	2 126	3 151	5 277	16 204
	**6. Green Office Meudon** 2011, Meudon (Paris), France, 48° 48′ 49.72″, lat. 48.81; Cfb PEB, office BBC-effinergie [65]	21 500	4 006	3 999	11 545	15 5444	83 119
	**7. Green Office Rueil (Ouest)** 2015, Rueil Malmaison, France, 48° 52′ 58.0′', lat. 48.88; Cfb, PEB, office Bepos Effinergie 2013, BREEAM Very Good [66,67]	14 997	2 849	2 576	9 047	11 623	70 513

(continued on next page)

Table 1 (*continued*)

3D model [1]	Case study data and location	Geometrical data					
	Year, location, coordinates, latitude (DD), climate zone, PEB/NZEB, awards/certifications, data sources	Net floor area m^2	Building footprint m^2	Roof area m^2	Façade area m^2	Envelope area[2] m^2	Volume m^3
	**8. Arkinova Activity Generator** 2016, Anglet, France 43° 28′ 53.05, 43.48; Cfb PEB, office Bepos Effinergie 2013, HQE, BREEAM Pass [68,69]	1 800	1 236	1 298	1 461	2 759	8 808
	**9. Pépinière d'entreprises (Business Incubator)** 2018, Montlieu la Garde, France 45° 14′ 45″, 45.25; Cfb PEB, public office BEPOS + effinergie 2017-E4C1 [70]	604	635	649	629	1 279	2 216
	**10. Elithis tower** 2009, Dijon, France 47° 19′ 0.01″, 47.32; Cfb NZEB, office [65,71–73]	4 567	419	499	3 119	3 617	15 368
	**11. Pixel building** 2010, Melbourne, Australia −37°48′50″, 37.84 (S); Cfb NZEB, office LEED Platinum [74,65,75]	837	275	275	913	1 188	3 095
	**12. The Zero Building** 2013, San Sebastian, Spain 43°17′30.52″, 43.31; Cfb NZEB, office LEED Gold, BREEAM Excellent [76]	9 160	3 185	5 044	5 799	12 939	53 366
	**13. UBA** 2013, Berlin, Germany 52°31′27″, 52.52; Dfb NZEB, administrative [77]	1 178	663	813	838	1 650	5 072

1- All the images have the same scale.
2- Total envelope ratio (roof + façade area).
*According to the Köppen-Geiger climate classification map, Trondheim is situated at the interface of oceanic (Cfb) and subarctic (Dfc) climates [78], according to other sources Trondheim is situated between continental (Dfb) and Dfc climate zones [43], or subpolar oceanic (Cfc) and Dfb [79].

The scope of the search included mostly European certification databases such as DGNB (Germany) [46], Klimaaktiv (Austria) [47], Building of Tomorrow [48] and Bepos (France) Observatoire BBC (Effinergie) [49] These contain statistical information and many of the projects with available energy data are located in oceanic and continental climates (Cfb/ Dfb climate zone). Most of the study cases were found on the official websites of ZEB [50], EXCESS [51], as well as in scientific conferences and NZEB PEB websites, such as MonitorPlus Leitprojekte [52], Cravezero [53] and the IBO- Austrian Institute for Construction and Ecology. In addition, the Construction21 website [54]

Table 2
Energy data.

Project	Data type[1]	RE generation sources[2]				Primary energy generation	Primary energy heating	Primary energy cooling	Primary energy electricity	Total primary energy consumption
		PV	ST	HP	CHP	kWh/m^2.yr				
1. Powerhouse Brattørkaia	R + S	•		S		33.70	4.40	0.00	22.70	27.90
2. Freiburg New City Hall	R	•	•	G	x	63.50	17.10	0.90	46.30	64.30
3. Aspern IQ	R + S	•		G		50.40	21.60	7.36	–	50.82
4. Windkraft Simonsfeld AG	R + S	•	•	G		127.00	4.20	0.00	91.20	111.00
5. ArcheNEO	R	•		G		34.88	–	–	–	32.15
6. Green Office Meudon	R	•			•	101.00	33.80	1.60	37.40	88.56
7. Green Office Rueil (Ouest)	R + S	•		G		57.00	11.50	7.40	27.40	46.30
8. Arkinova Activity Generator	R + S	•		A		34.28	–	–	–	26.20
9. Pépinière d'entreprises	S	•		A	•	125.40	38.50	4.60	23.60	66.70
10. Elithis tower	R	•			•	40.67	11.00	10.00	35.50	65.00
11. Pixel building	R	•			x	84.00	8.40	75.20	39.40	123.00
12. The Zero Building	R	•	•	G	•	15.62	3.80	3.87	12.65	20.31
13. UBA	R	•	•	G		150.60	21.85	10.26	69.50	96.70

1- R- real, S- simulated (obtained from above mentioned websites).
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).

Table 3
PV system data.

Case study	GHI[1] kWh/m^2.yr.	PV system[2] Roof/façade	Data type Real/sim	Installed PV area PVm^2	Installed PV roof area m^2	Installed PV façade area m^2	Peak power kWp	PV generation kWh/yr	PV generation/m^2 kWh/m^2.yr.	Self-sufficiency Egen/Econ, in %
1. Powerhouse Brattørkaia	747	Ri + F	R + S	2867	1886	981	576.88	481 000	33.00	120.7
2. Freiburg New City Hall	1093	R + F	R	2164	185	1848	682.00	1 385 000	63.50	98.8
3. Aspern IQ	1122	R + F	R + S	1061	1300 total	–	144.80	369 230	50.40	99.2
4. Windkraft Simonsfeld AG	1122	R + F	R + S	382	242	137	47.00	110 092	127.00	114.4
5. ArcheNEO	1146	R + F	S	1300	1300	–	204.78	226 750	34.88	108.5
6. Green Office Meudon	1068	Ri + F	R	4200	2100	2100	601.50	–	101.00	114.0
7. Green Office Rueil (Ouest)	1068	R	R + S	1904	1715	0	362.94	–	57.00	110.5
8. Arkinova Activity Generator	1265	R	R + S	600	190	0	59.00	–	34.28	130.8
9. Pépinière d'entreprises	1265	R	S	161	161	0	29.10	75 742	125.40	170.8
10. Elithis tower	1178	Ri	R	560	456	0	82.00	181 100	39.65	62.6
11. Pixel building	1583	R	R + S	38,4	38,4	0	6.30	19 965	23.88	68.3
12. The Zero Building	1171	Ri	R	1291	1291	0	230.00	273 380	15.62	76.9
13. UBA	985	R	R	391	391	0	66.30	177 351	150.55	155.7

1- Global horizontal irradiation (GHI): Long-term yearly average of yearly totals expressed in kWh/m^{2}yr, obtained from the Energy Plus weather database for the capitals of regions.
2- R- roof, Ri- roof integrated F- façade.
3- R- real, S- simulated.

was used to obtain measured energy data. The paper focuses on case studies found during previous research into the topic of PEB [40]. In February 2023, more recent energy data were obtained for some of the buildings.

Most of the buildings (except Pépinière d'entreprises) have real monitored energy data. The simulated results are expressed in primary energy and for a time span of one year. The energy simulations were made by the buildings' designers in accordance with national building energy codes (for case studies located in France- RT 2012 - E + C, Germany- The Energy Saving Ordinance (EnEV), Austria- OIB - Richtlinie 6). The Pixel building's energy performance was modeled using the Indoor Climate and Energy simulation tool during its design process. For the Powerhouse building, the measured PV production and calculated demand data by Skanska were used in the research. It has to be noted that the validity of the data is based on the reliability of the referenced sources, which may embrace a level of uncertainty in the simulations and possible errors in the measurements that are out of the scope of this research.

The common geometrical feature of all the case study buildings is their compact form along with an optimized orientation and envelope. Net floor area and envelope are found to be key factors to define a building's compacity from the design point of view. The initial form of

Table 4
Basic Ratios.

Case study	Basic Ratios								
	Compacity V/A m^3/m^2	**HEI** m^2/m^2	**Roof/ façade** m^2/m^2, in %	**Self-sufficiency** Egen/Econ, in %	**PV m^2r/PV m^2faç** m^2/m^2	**PV r-con** m^2/m^2, in %	**PV r-env** m^2/m^2, in %	**Power per m^2 net floor area** Wp/m^2	**Egen/ GHI** %
1. Powerhouse Brattørkaia	6.18	5.87	31.7	120.7	1.92	20	32	40.4	4.4
2. Freiburg's New City Hall	5.83	4.86	31.7	98.8	0.17	10	17	31.3	5.8
3. Aspern IQ	4.47	2.89	52.4	100.0	–	14	16	19.8	4.5
4. Windkraft Simonsfeld AG	1.68	1.54	55.4	114.4	1.77	44	13	54.2	11.3
5. ArcheNEO	3.07	3.06	67.5	108.5	–	20	25	31.5	3.0
6. Green Office Meudon	5.35	5.37	34.6	114.0	1.00	20	27	28.0	9.5
7. Green Office Rueil (Ouest)	6.07	5.26	28.5	110.5	x	13	16	24.2	5.3
8. Arkinova Activity Generator	3.19	1.46	88.9	130.8	x	33	22	32.8	2.7
9. Pépinière d'entreprises	1.73	0.95	103.2	170.8	x	27	13	48.2	9.9
10. Elithis tower	4.25	10.91	16.0	62.6	x	12	16	18.0	3.5
11. Pixel building	2.61	3.04	30.1	68.3	x	5	3	7.5	1.5
12. The Zero Building	4.12	2.88	87.0	76.9	x	7	10	25.1	1.3
13. UBA	3.07	1.78	97.0	155.7	x	33	24	56.3	15.3

– no data available for PV area.
x the building has no PV on the façade, therefore the ration cannot be calculated.

the building also limits the area for integrating PV systems on either the roof or the façade. Therefore, the study assesses the following aspects: location, form and massing.

C) Obtained data grouped by field

The data available from reliable case studies is summarised in three tables (Tables 1, 2 and 3). This stage should be understood as an open data base where more buildings and data could be further introduced to enrich the presented research procedure, outcome and conclusions.

The obtained data are listed below, grouped by **field**:

Geometrical features (see Table 1).

- Net floor area [m^2]
- Building footprint [m^2]
- Roof area [m^2]
- Façade area [m^2]
- Envelope area [m^2]
- Volume [m^3]

Location related data (see Table 1)

- Latitude [degrees]
- GHI [kWh/ m2.yr]

Energy and photovoltaic system data (see Table 2)

- Energy generation [kWh/ m^2.yr]
- Energy consumption [kWh/ m^2.yr]

Photovoltaic system data (see Table 3)

- Total installed PV area [m^2]
- PV roof area [m^2]
- PV façade area [m^2]
- Peak power [kWp]

To obtain geometrical data (building footprint and envelope areas, as well as volume), the case studies were modelled in 3D CAD software. The selected buildings represent the diversity of design options for buildings located in different latitudes although within the same climate zones. 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. The energy generation and consumption data are expressed in primary energy units, as originally calculated for each applicable national code.

D) Basic Ratios

At this stage, case study input data are combined to calculate basic ratios. Basic ratio refers to a building's characteristic parameter expressed in a numerical value that is used to define and analyse the case studies. Some of the ratios are used to define a building's design properties (compacity, energy self-sufficiency) (e.g., used in [55,36]), others are established according to the objective of the study (several PV-related ratios). The basic ratios are summarized as follows, each having a corresponding graphic in Section 4.1:

- Compacity (volume/envelope area) [m^3/m^2]
- HEI (net floor area/ occupied) [m^2/m^2]
- Roof/façade area relation [m^2/ m^2], in %
- Energy self-sufficiency (Egen/Econ), in %
- PV roof to façade area [m^2/ m^2]
- PVr-con, PV area to net floor area [m^2/ m^2], in %
- PVr-env, PV area to envelope area [m^2/ m^2], in %
- PV system's peak power per net floor area [Wp/m^2]
- Energy generation and GHI [kWh/ m^2.yr]

Compacity (volume in m^3/ envelope area in m^2) - or inversely the form factor (m^2/m^3) - and height index (HEI) (the relation between net floor area and the building footprint) are the first of the basic ratios. Compactness and the HEI factor are related to building shape and affect the possible placement and integration of PV. In addition, the HEI factor is useful for assessing plot occupation in urban contexts. Roof to façade percentage shows the proportion between roof and façade area of a building. This ratio helps to identify whether higher PV façade integration is required or not, especially in high rise buildings, where a smaller roof area is available. Onsite PV energy generation is indispensable for PEB and NZEB buildings aiming to achieve a good energy self-sufficiency ratio. PV area to net floor area defines the size of the PV system in relation to building's scale. PV area to envelope area is the amount of the building envelope used for solar energy harvesting. The PV peak power per net floor area ratio identifies the installed power density for this type of buildings. Therefore, proposed PV ratios could serve as an approximation to the dimension of the PV system prior to calculations. The available irradiation and latitude (and consequently solar altitude) also affect PV placement and its integration in the building.

E) Key performance indicators that relate different fields (location, geometry, energy and photovoltaic)

The generated KPIs aim at relating building data from different fields that are usually disconnected, e.g., architects design a form, the engineers simulate the building and introduce PV where possible, while the location is usually a given data. This research is an attempt to unveil the connections among these fields that need to be well coordinated and taken into account since the beginning of the project by architects for a successful PEB project. Therefore, the data from the fields combined are shown in the section 4.2 in a series of graphics from Figs. 10 to 21.

The basic ratios are combined in graphics to identify the correlation between them (Section 4.2). Therefore, the KPIs are established graphically as combinations between the basic ratios. The elaborated KPIs and their optimal value ranges are used to assess the case studies by defining their actual performance and potential improvements.

F) Analysis and discussion

The trends highlighted on the graphics visualize the impact of specific design decisions (e.g., compact building shape or the PV integration in the façade). Two approaches are applied in the trend line based analysis of the graphics. The first one, used for trend lines with $r^2 \geq 0.6$, focused on the tendencies obtained from the trend line. This trend line based analysis is applied in all of the graphics in section 4.1, except Fig. 9 that required other type of analysis. As for Fig. 4, no trend line was added because the line of 100% self-sufficiency was considered more relevant. The second approach was applied mostly in Section 4.2 to figures that were considered of higher interest for the research. In these cases, trend lines divide graphics in two or more regions and help to form groups of values. Moreover, they mark medium values and serve as a guideline to detect other types of trends and absolute values. Discussions and partial conclusions are offered together with each of the figures.

Based on the outcomes and the impact of each of the basic ratios, relevant KPIs are highlighted and discussed in Section 5.

G) Decision making framework and conclusions

The proposed framework offers a sequential and chronological method to be implemented in the early PEB design process. This aims at improving current architecture design decisions that at taken in a non-integrated manner between architecture and engineering teams. These conclusions should be understood as an outcome made possible by the available data out of the analysed case studies. Therefore, this method of analysis is open to more input data that will help refine the conclusions.

The established KPIs serve several purposes. First, they make possible to assess the design options to understand better each building's possibilities and limitations to integrate PV systems. Secondly, the identification of the average values and ranges allows to group and to

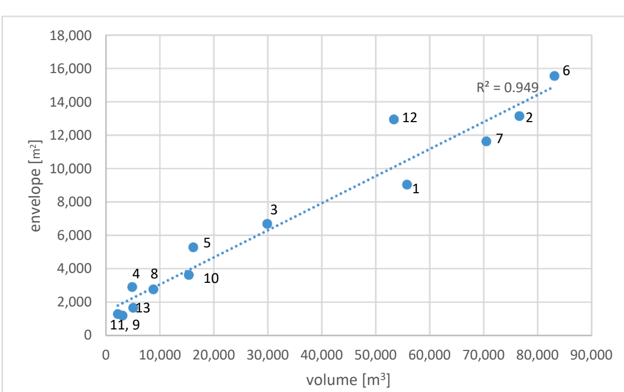


Fig. 1. Building envelope area vs volume.

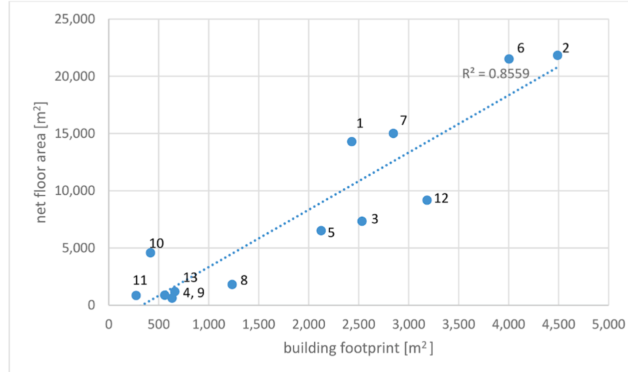


Fig. 2. HEI factor.

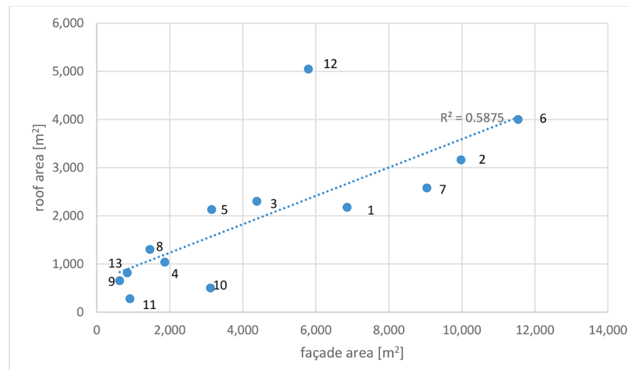


Fig. 3. Relation of the roof area to the façade area.

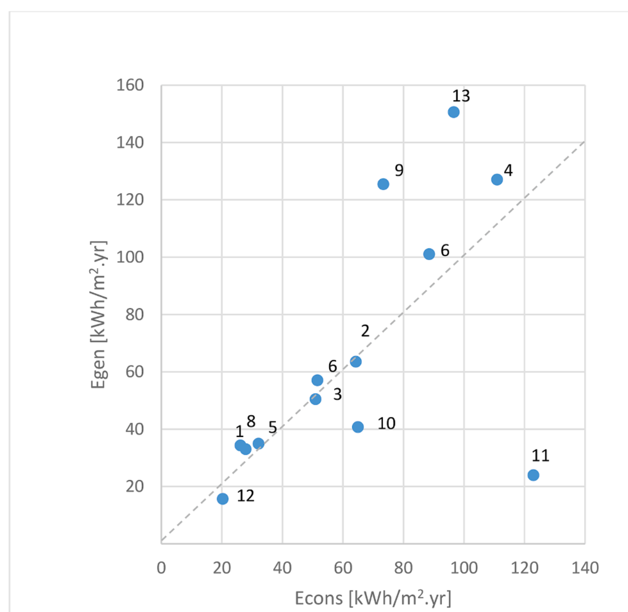


Fig. 4. Relation of energy generation to energy consumption.

preview the potential success of the designs as PEBs and energy self-sufficient buildings. Moreover, the building parameters that fall out of the ranges can be easily identified, which is helpful for problem solving and evaluating potential improvements in the design. Thirdly, the outcomes are resumed in the form of a decision-making methodology for building design. Therefore, the research could provide useful guidelines for the design of office buildings that aim to achieve positive balance,

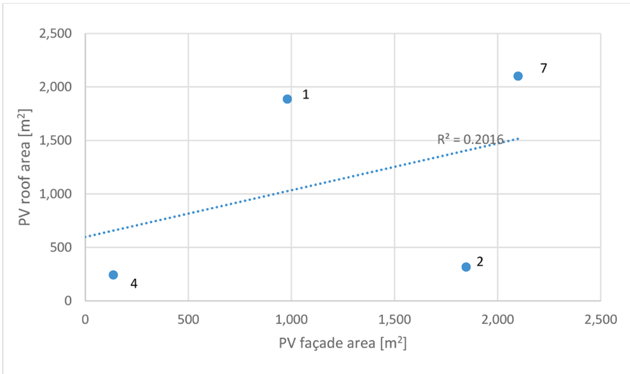


Fig. 5. Relation of the area of the PV system installed on the roof to that on the façade.

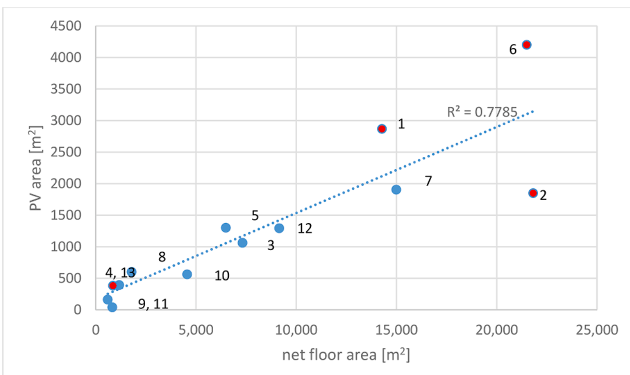


Fig. 6. Photovoltaic area to net floor area ratio.

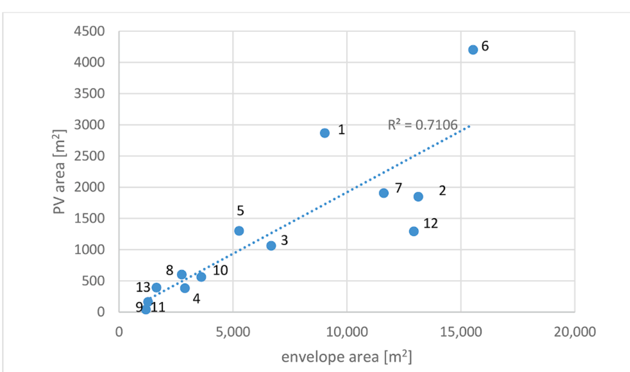


Fig. 7. Photovoltaic area to envelope area ratio.

specifically in the early design stages prior to simulations or parametrization. This methodology could further be adapted to other architectural types, like educational buildings.

3. Case study buildingś architectural design, energy performance and PV system data

3.1. Geometrical and architectural design

Table 1 introduces the case studies and provides a 3D model picture of each of the case study buildings drawn at the same relative scale and with the same orientation. The available general data are location, latitude, and the climate zone data are taken from the webpage [56] and are based on ECMWF data. The building use, net floor area, certifications

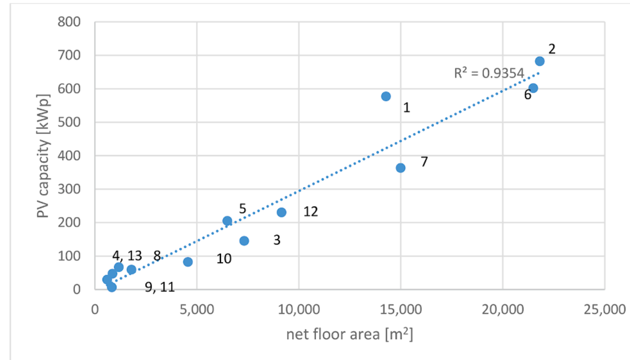


Fig. 8. Relation of the installed PV capacity to the net floor area.

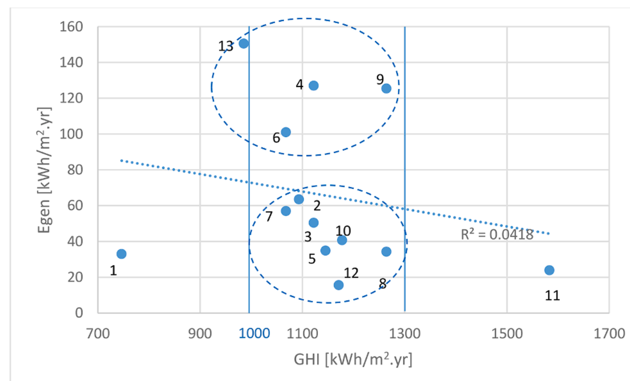


Fig. 9. Relation of the generated PV energy to GHI.

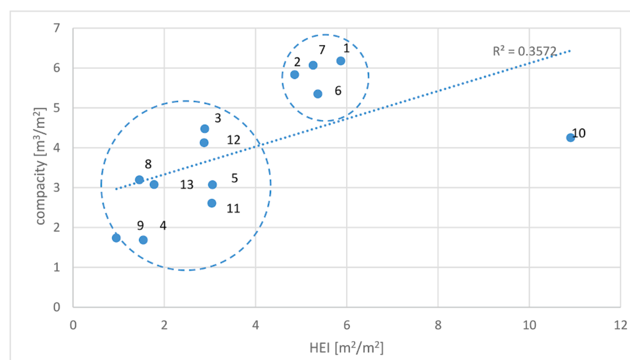


Fig. 10. Relation of the building compacity to HEI.

and data sources are also presented in the table. From the generated 3D models, the footprint, roof, façade, envelope area and volume of the buildings are obtained. Net floor area refers to the area of the building that is climatically conditioned (net floor area column in Table 1).

3.2. Energy performance

The energy data (energy generation sources and homogenized energy performance indicators) for the following case studies is shown in Table 2. Most of the cases measured and verified performance data is found in primary energy and given for the time span of one year. For one of the cases, only simulated data was available (Pépinière d'entreprises), while for the others both simulated and real data was found. To compare the generated and consumed energy of the analysed buildings, the data was processed for homogenization of the values: the final energy was

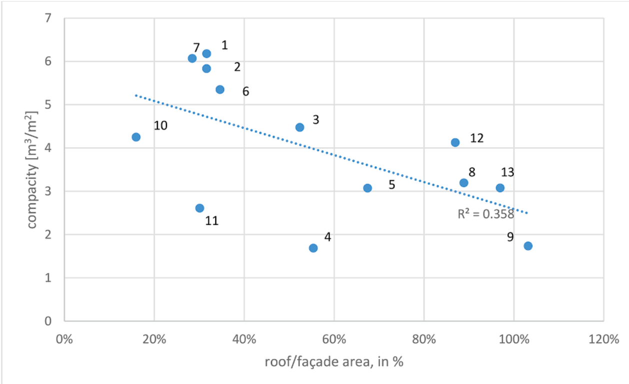


Fig. 11. Relation of the building compacity to roof/façade ratio.

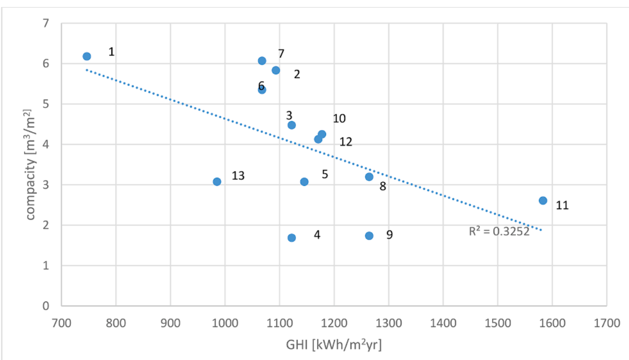


Fig. 12. Relation of the building compacity to GHI.

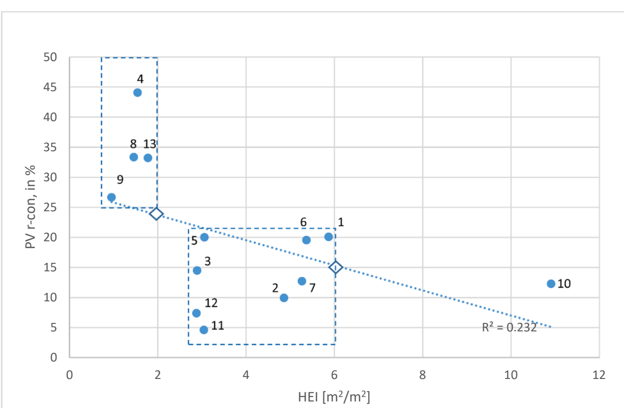


Fig. 13. Relation of PV r-con (photovoltaic area to net floor area ratio) to HEI (height factor) [m^2/m^2].

transformed into primary energy applying the weighting factors published by the Ministry for the Ecological Transition and the Demographic Challenge of Spain (MITECO) [80]. Heating, cooling and electricity energy consumption, as well as renewable energy generation based on monitored or simulated data, is expressed in primary energy use in kWh/m^2yr. Primary energy considers the difference in generation and distribution by different energy carriers. Therefore, in the context of decarbonization objectives, savings in primary energy are more important than savings in final energy, and are used more as balance metrics in PEB assessment [11].

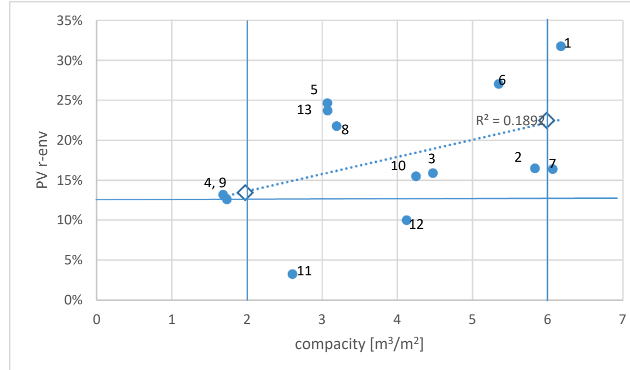


Fig. 14. Relation of PV r-env (photovoltaic area to envelope area ratio) to compacity (m^3/m^2).

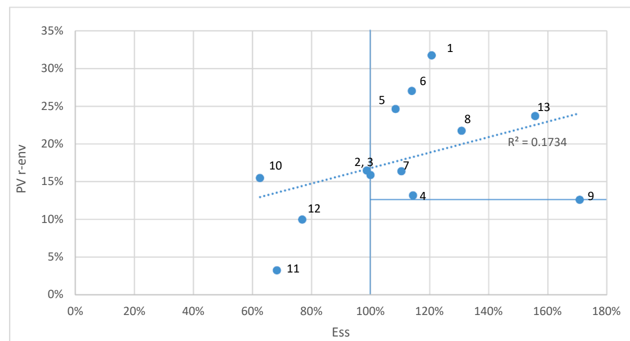


Fig. 15. Relation of PVr-env to energy self-sufficiency.

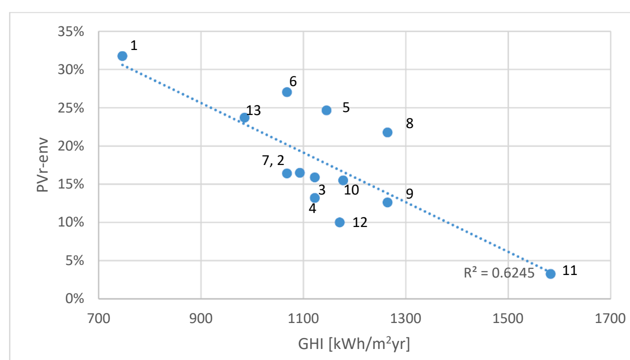


Fig. 16. Relation of PVr-env (m^2/m^2) to GHI.

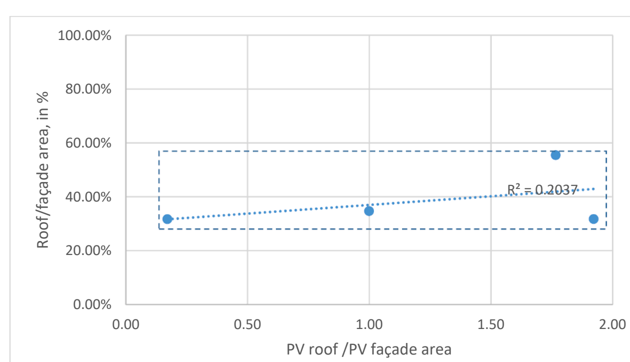


Fig. 17. Relation of roof/façade ratio to installed PV roof/façade area.

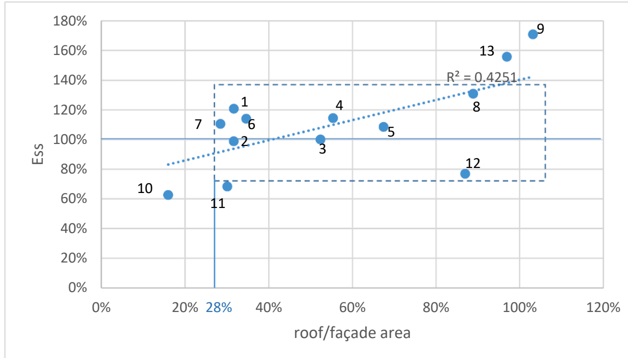


Fig. 18. Relation of energy self-sufficiency to roof/façade area ratio.

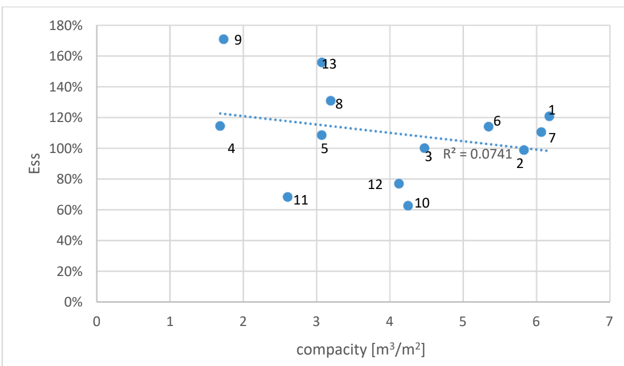


Fig. 19. Relation of energy self-sufficiency to compacity.

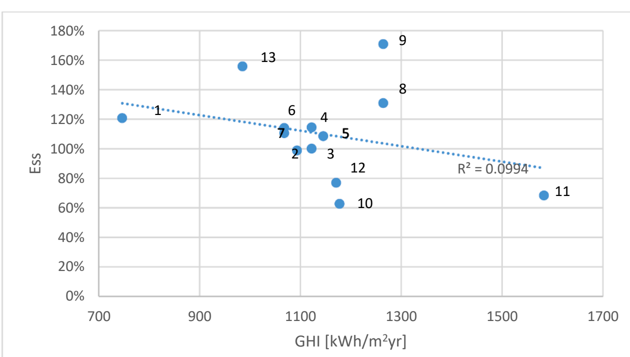


Fig. 20. Relation of energy self-sufficiency to GHI.

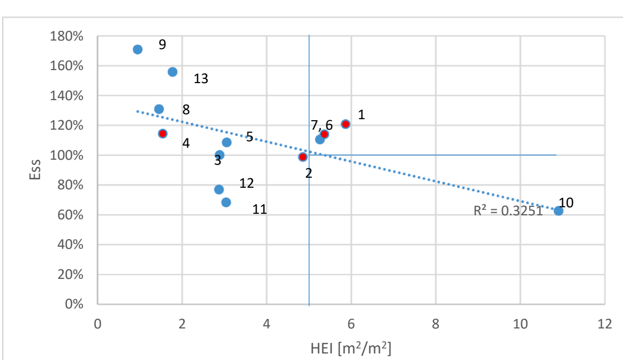


Fig. 21. Relation of energy self-sufficiency to HEI.

3.3. *Photovoltaic system*

Table 3 introduces data related to photovoltaic electricity generation, such as installed PV area, PV energy generation and global horizontal irradiation (GHI) available in the region. Moreover, the self-sufficiency ratio is derived from the data in Table 2.

As shown in Table 3, most of the buildings positioned as PEBs generate an energy surplus of more than 8% from photovoltaics on balance over a year. It should be taken into account that for two of the PEBs only simulated energy data is analysed. NZEBs compensate between 27.7 and 155.7% of the consumed primary energy. Self-consumption of the generated energy was not considered.

The performance of the PV on the façade is not usually as good as that on the roof, but it contributes necessary energy 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 relevant matter of interest in early design stages and could be further researched.

Six out of the thirteen buildings have PV systems installed on the façade in addition to the roof. For four of them, PV façade and roof area data are available (Powerhouse Brattørkaia, Windkraft Simonsfeld AG, Green Office Meudon and Freiburg New City Hall).

4. Results and discussion

The goal of the research is to propose a decision-making tool for PEB design that takes into account a range of factors related to building geometry, energy performance, photovoltaic integration and location. The use of real case studies to generate novel ratios and illustrate the proposed method confirms the studýs findings.

In the first stage, raw data from the literature and geometry measurements were collected and processed as previously shown in Tables 1, 2 and 3. Then, basic ratios were generated from the direct relations between these data, as shown in Table 4. The basic ratios refer to data relations within the domains of the three areas previously identified in the tables, i.e. building geometry, energy performance and the PV system.

The KPIs proposed later will refer to relations between these basic ratios, which will combine data from different areas. The aim of the KPIs is to unveil more intricate relations among the different areas that affect a holistic PEB design approach at an early design stage.

4.1. *Basic ratios for building geometry, energy performance and photovoltaic systems in PEBs*

4.1.1. *Volume of the building and the building envelope area*

Compacity (volume in m^3/ envelope area in m^2) - or inversely the form factor (m^2/m^3) - is a design factor of high relevancy in terms of the energy efficiency of buildings. A smaller envelope surface means less energy losses and reduces the energy demand of the building. A high index means better compacity (a sphere would be the most compact shape), and a lower index implies a high amount of envelope for the same enclosed volume.

For temperate climates, where the research is focused, a smaller envelope surface for the same enclosed volume allows energy losses to be reduced. Nonetheless, a high compacity implies a reduced area of roof and facade, which may limit the integration of surface PV in the building envelope. The form of the volume is also affected by the solar exposure of the façade and roof. For the same compacity figure, low rise buildings can harvest more solar energy on the roof, and their performance is linked to location factors such as the latitude or the global horizontal irradiation.

4.1.2. Height factor (m^2/m^2)

The height of the building is a relevant factor in urban areas, as it is linked to the density [81]. Generally, the density index is referred to as the floor area ratio (FAR), which relates to the gross floor area (GFA) divided by total area of the plot. As the plot can be very variable, the coverage (COV) index defines the relationship between the covered area on the plot and the total area of the plot. In this context, height factor (HEI) can be defined as an index dividing FAR by the COV [82]. Hence, HEI (m^2/m^2) defines an average height that relates the floor area and the building footprint. For the purpose of this research, an index with no link to any specific plot area is preferred, because the goal is to study the buildinǵs relative density for a given footprint area without limiting its form and height.

The graphic shows the relation between net floor area (m^2) and the occupied area of the building (m^2) for each building. The trend line indicates a mean relation between both data sets. For the following graphics, a numeric value has been taken for HEI, as indicated in Table 4.

4.1.3. Relation of the roof area vs. the façade area

This geometrical ratio relates the roof area of a building and its façade area. This aims to define an available surface for subsequent BIPV integration, and is directly defined by the architectural design.

In this research, inclined surfaces have been considered roof planes if their inclination is below 20° to the horizontal plane, and the measured area corresponds to its real magnitude. The building with the highest roof area is Zero Building that uses its singular cylindrical form that is partly sunk to optimize PV integration and maximize energy generation.

4.1.4. Energy self-sufficiency ratio

The graphic shows the energy generated on site by means of BIPV on the roof and façade (Egen), alongside the consumed energy (Econs). The consumed energy refers to the operational energy of the building, i.e., the energy that is used during the occupancy stage of the life cycle of a building for space and water heating, space cooling, lighting, running the equipment and appliances, etc. (Azari 2019). These data have been collected from specialized literature and homogenized for this research, as mentioned before.

It is easy to see that the buildings situated above the diagonal line are positive energy buildings that generate more energy than they consume, whereas those below the line did not achieve this distinction as they are not able to produce the amount of energy they consume. This may be due to two main reasons: on the one hand, this study is based on real measured data and not on simulated data; on the other hand, the commissioning and the performance gap assessment often affects the actual performance of buildings. During commissioning activities, many decisions can be made to reduce building energy consumption by up to 15% and help buildings to meet design goals [83].

4.1.5. PV area installed on the roof vs. PV area on the façade

For the office building typology in temperate climates, the ability to generate its own electricity on-site is an important factor to achieve self-sufficiency. Therefore, the photovoltaic system has a decisive impact on the design of the building. Six of the 13 buildings have incorporated PV modules on their façade, but PV façade area data is available only for four of them. Previous research showed that a photovoltaic system on the façade, despite its relatively low contribution to the total solar energy gain (approx. 18% in Freiburg and approx. 22% in Brattørkaia), is decisive for reaching a positive energy balance [40]. The graphic shows the total PV area for each case study and the area divided into roof and façade.

4.1.6. Overall PV area of the building vs. its net floor area

This ratio helps to predict the PV area needed according to the building's floor area in the early design stage. This includes both roof and façade PV systems, taking into account a mean monocrystalline panel performance. The linear trend line shows an average ratio of PV panel surface equivalent to 15% of the floor area of the building. Large buildings in dense urban zones require compact building shapes that enable optimizing land area use, but they usually have low roof area to envelope area ratio, which makes it more difficult to achieve energy self-sufficiency. The buildings that incorporate PV panels on their façades have been highlighted in the graphic as red dots, and it can be observed that the biggest buildings incorporate this solution.

4.1.7. Photovoltaic area vs. envelope area ratio

This ratio shows the amount of building envelope used for solar energy harvesting, and is related to the façade and roof design. Floor plan design and optimization is key to maximize the area for PV panels integrated on the roof. The trend line of the graphic shows that around 20% of the envelope area is used for PV panel integration. This is clear evidence of the impact that the BIPV has on the architectural image design, and that PV solutions need to be part of the design of PEBs. In other words, the photovoltaic module becomes a construction element and more building components must include solar PV cells. The percentage of window openings and opaque areas is also relevant, and also mixed solutions such as glazed PV surfaces are possible, but they do not apply for the case studies of the research.

4.1.8. Installed PV capacity vs. the net floor area of the building

For the selected case studies, the trend line shows a mean installed capacity of the PV system of 30 Wp/ m^2. The building that stands out most from the average figure is Powerhouse Brattørkaia with 40.4 Wp/ m^2.

4.1.9. Energy generation from PV panels per net floor area (Egen) vs. irradiation (GHI)

The PEB case studies taken for this research portray a variety of design solutions, as shown in this graphic. Energy generation from PV panels per net floor area (Egen) can reach as high as 150 kWh/m^2y in some cases, but for an irradiation value between 1000 and 1300 that corresponds to Cfb and Dfb climate zones, a good figure for energy generation is above 70 kWh/m^2y. It is interesting to note that two main building groups may be identified, one below this figure, and another one with an energy generation above this figure, including buildings with extensive horizontal roofs. Their high PV energy generation is related to high installed power per m^2 and high PVr-env ratios. It is interesting to note, that the building situated in the most favourable situation according to GHI availability resides well beyond the expected generation, and thirdly, that a building located in a place with a very scarce GHI can achieve the recommended energy generation.

4.2. Proposed KPIs

The KPIs proposed refer to relations between the previous basic ratios, which combine data from the areas of building geometry, energy performance, PV system areas and location. As mentioned before, these novel KPIs aim at framing useful trends for decision-making at the early stages of PEB design.

4.2.1. Compacity vs HEI

This KPI relates the compacity of the building with its height index HEI. The higher the building, the more envelope surface it will have.

This graphic shows different building types according to their geometrical design, helping to identify strategies to achieve PEB designs. A low HEI value (up to 3) refers to typically branched low-rise buildings that may have a relatively high roof area with a low compacity. In contrast, another group of the case studies can be identified with greater compacity and higher HEI values (up to 6), these being medium-rise compact buildings. There is one building that stands out for having a high HEI and a medium compacity, namely the Elithis Tower.

4.2.2. Compacity vs roof/façade area ratio

The higher the compacity, the less roof per façade area there is in the design of the selected PEB case studies. Less compact buildings may incorporate more PV panels on the roof, while they may get more energy losses because of their higher envelope proportion value.

In conclusion, buildings that are more compact have a higher amount of façade area, so the design approach for solar energy harvesting should take the façade into account.

4.2.3. Compacity vs GHI

The graphic shows the relationship between compacity and global horizontal irradiation (GHI) for the studied PEB buildings. The buildings follow the trend of having a more compact shape in areas with a lower GHI, where the energy losses are higher. On the contrary, where GHI index is higher, the design of the buildings is less compact as less energy is lost during cold periods and more solar energy harvesting is available.

4.2.4. Photovoltaic area to net floor area ratio vs HEI

This graphic relates the following two factors: the ratio of the photovoltaic panels area and the net floor area of the building, called PV r-con (m^2/m^2) and the height factor HEI (m^2/m^2).

Buildings with a low HEI (up to 3) can be considered low-rise buildings for this study. They tend to have a higher PV ratio per floor area, mainly because they have a higher roof-façade percentage.

A HEI factor that is close to 6 may also permit a photovoltaic area integration ratio (PVr-con) of 20%, as is the case of Powerhouse Brattørkaia. The building design was shaped modelling conventional roof and facade plans and inclining them to achieve an optimum angle for solar irradiation. The Zero building is another example of this design strategy [76].

4.2.5. Photovoltaic area to envelope area ratio vs compacity

The PVr-env (PV total area/total envelope area, in %) is a ratio that shows the extent to which the envelope of the building is used as a solar energy harvester. More compact buildings have a smaller relative surface of envelope, so greater optimization of the envelope is needed to achieve energy self-sufficiency. Five of the case study buildings use more than 20% of their envelope for BIPV, one reaching 27% and another almost 32%. These examples include PV panels in their façade. A good figure for this ratio will be close to the defined by the trend line by these two points:

For Compacity 2 = PVr-env 13%
For Compacity 6 = PVr-env 22%

A bottom line indicating a PVr-env ratio of 13%, which incorporates 11 out of 13 case studies, can be identified in the graphic.

4.2.6. Photovoltaic area to envelope area ratio vs energy self-sufficiency

The PV integration ratio on the envelope is above 15% for all the buildings that achieve 100% self-sufficiency, except 2 buildings that have PVr-env ratio of 13%.

4.2.7. Photovoltaic area to envelope area ratio vs GHI

Global horizontal irradiation (GHI) provides a simplified approximation to the potential for PV power production and allows a comparison of the available natural conditions without considering a particular technical design and mode of operation. The trend line shows that buildings located in sites with a low GHI have a higher PV area ratio of their envelope and, reversely, in locations with high GHI the PV area ratio of the building envelope is lower.

4.2.8. Roof/facade ratio vs roof/façade PV area

This graphic shows the relation between the roof to façade area ratio of a given building design and the proportion of PV panels integrated into the roof and façade. Among the case study buildings taken for this research, only a few incorporate PV panels on the façade, but it is possible to identify a common trend that identifies a roof-faç ratio between 30% and 60%. A higher roof-faç ratio would mean that the building's façade is relatively small and less relevant compared with the roof area.

4.2.9. Energy self-sufficiency vs Roof-faç%

As seen from the graphic, a higher roof to façade ratio facilitates achieving a better energy self-sufficiency ratio. The PEB building case studies that have self-sufficiency of 100% or higher, and thus are truly energy positive, have a roof-faç ratio over 28%. This would suggest that, according to the research conducted, this roof area percentage is a bottom line for PEB design.

4.2.10. Energy self-sufficiency vs compacity

Buildings with a higher Ess% are more likely to be designed with a lower compacity value. Nonetheless, the energy demand of these buildings is also higher as they have a higher envelope surface.

Achieving a high Ess% onsite with a high compacity is more difficult due to a tighter PVr-env factor. The trend shows that the compacity range for the selected case studies is wide, ranging from 1.5 to 6.2, but the Ess% for buildings with a higher compacity are only slightly above 100%.

Therefore, it can be concluded that high compacity and HEI are factors that may limit the achievement of a high Ess% in office PEB designs.

4.2.11. Energy self-sufficiency vs GHI

Locations with a low GHI generally have a colder climate and need to take more advantage of the solar energy available. Seven of the thirteen case studies are located in places with a GHI ranging from 1068 to 1178 kWh/m^2yr, and most of them achieve self-sufficiency. The building that yields a better balance while located in a low GHI zone is Powerhouse Brattørkaia, because it is able to achieve a self-sufficiency value of 120%. In addition, at lower latitudes, where the sun does not rise high, buildings have to get more energy from the façade than from the roof. This underlines the need for high buildings to incorporate mixed shapes where the façade and the roof blur, creating building forms with inclined surfaces in their envelope. This graphic reveals that there is a great potential in sunnier countries that is yet to be exploited, as could be the case of the Pixel building.

4.2.12. Energy self-sufficiency vs HEI

The self-sufficiency ratios are higher in the low height index (HEI) case studies. Self-sufficiency is achieved in the designs up to a HEI of 6. From the design point of view, the higher the HEI factor, the harder it can be to achieve a high percentage of energy self-sufficiency due to the lack of available roof surface. It is worth noting that three of the four buildings with the highest HEI that achieve self-sufficiency goals integrate PV panels on the façade (dots in red). Therefore, it can be concluded that the higher the HEI, the harder is to achieve self-sufficiency goals. Thus, beyond a HEI ratio of five, the façade needs to be taken into account as solar collector in the design of the building.

5. Decision-making design framework for PV system integration in positive energy buildings

Designing a building implies finding a balance among many different approaches. PEBs will help mitigate the global environmental challenge by drastically reducing CO^2 emissions, and are able to produce the required energy onsite. This consideration needs to be part of the architectural design process and should also facilitate the achievement of the goal of becoming a PEB from the early design stages, when this kind of decisions need to be considered. Therefore, a decision-making design framework based on actual tests is proposed that may help to make the design of PV systems for PEBs more effective. The framework is based on the previously studied ratios and KPIs specifically designed for PEBs and BIPV systems.

The implementation sequence defines several steps to be followed during the typical decision-making sequence in a PEB project design:

1- The architectural design process commonly begins by studying the given situation of the plot and deciding on the built floor area and the **footprint** of the building. The parameter that relates the two factors at a building scale is the height index (**HEI**). According to the research conducted, the locations of the studied PEBs follow a mean trend line. The self-sufficient PEBs analyse present a HEI factor ranging from 1 to 6. (see Fig. 2) Fig. 3.

2- Introducing **form** implies taking architectural design decisions relating to the volume and the envelope of the building, and the factor **Compacity/HEI** gives a feasible ratio. As seen from the research, it is necessary that PEB designs will take into account one of the trends identified in the present study, i.e., either a low HEI and low compacity, or a high HEI and high compacity design. (see Fig. 10)

3- A key goal for PEBs is to achieve **energy self-sufficiency (Ess%)**. At this point, it is interesting to contrast the HEI factor with the Ess% of the case study buildings to find the possible limitations derived from the geometrical design. As mentioned previously, a **HEI factor > 5** will require BIPV to be included in the façade design. (see Fig. 21)

4- According to the case studies, only buildings with a **roof-faç area** ratio higher than 28% achieved 100% self-sufficiency. The correlation of these two factors is directly proportional, i.e., the higher the roof-façade ratio, the higher the percentage of self-sufficiency that can be achieved (see Fig. 18).

5- The next phase in the decision-making process is to define **the area for PV systems** and their integration into the envelope of the building design, for both the roof and façade. The **Roof-Faç vs PVr/PVf** ratio defines the PV integration capability in the envelope of the building.

PEB design permits a wide range of the roof-faç ratios, but for the buildings that integrate PV panels on the façade, the roof-faç ratio should be between **30% and 60%** according to the case studies analysed (see Fig. 17).

6- The **PV surface referenced to the net floor area** of the building, **PVr-con,** is an interesting KPI to check in the PEB design. In buildings with a HEI below 3, the PV ratio referenced to the net floor surface of the building can be higher. According to the research, a good figure for this ratio will be one above the trend line in the interpolation between these points:

For HEI 2 = PVr-con 25 or higher
For HEI 6 = PVr-con 15 or higher

To achieve this, considering non-orthogonal building façade planes optimized for solar energy harvesting can be an interesting option from the designer's point of view (see Fig. 13).

7- The **PV surface referenced to envelope area** of the building, **PVr-env**, and **compacity** ratio are related in the KPI that gives information about the optimization of the building envelope. A good figure for this ratio will be close to the defined by the trend line by these two points:

For Compacity 2 = PVr-env 13%
For Compacity 6 = PVr-env 22%

As a rule, a PV area corresponding to 13% of the envelope is a necessary starting threshold to achieve a positive energy building (Fig. 14).

8- The capability of the envelope to achieve energy self-sufficiency is measured through the proposed KPI, **PVr-env/Ess%**. As seen in the research, none of the analysed buildings reaches 100% self-sufficiency with a PVr-env ratio lower than 13%. Most of the analysed case studies present values above 15%, the figure proposed as a minimum reference value. It is worth mentioning that as an extreme case, a building design with a PV area of 33% of the total envelope is achievable. The threshold value remains above the trend line of the graphic that rises towards a PVr-env of 20% for an Ess of 130% (see Fig. 15).

9- As a consequence of the previous design decision, the **installed power capacity** of the PV system should be above **30 Wp/ m^2**, including both roof and façade panels, as is indicated by the trend line (see Fig. 8).

10- This decision-making process concludes by checking the **expected energy generation** vs irradiation ratio with the KPI **Egen/GHI.** As concluded from the previous analyses, the energy generation figure for PEBs has to be between above 70 kWh/m^{2}y (see Fig. 9).

Outline of the decision-making framework.

KPI	PEB design range/ value	Comments
HEI	1–6 (most of the case studies)	If HEI ≥ 5 → BIPV is needed
Compacity to HEI relation	Low HEI to low compacity and vice versa	
Roof/façade area ratio	>28% to achieve 100% Ess	Roof/faç is directly proportional to Ess If roof/faç is **30–60%** → PV façade needed
PV r-con	For HEI 1 = PVr-con 25 or higher For HEI 6 = PVr-con 15 or higher	
PV r-env	≥15%, up to 33% ≥30%	>13 for compacity = 2 >15 for compacity = 6
Wp/m^2	+ 30	Including both roof and façade
Egen	+70 kWh/m^{2}y	PEB office

6. Conclusions

To meet the challenge of climate change, cities and buildings need to be energy generators that reach energy self-sufficiency by producing onsite at least the same amount of energy that is needed for them to operate, without the use of fossil fuels. PEBs are part of the solution for the near future, and architecture and energy should be considered in unison to shape new architectures with specific design inputs.

The effectiveness of positive energy building (PEB) design largely depends on a balanced approach between architectural design and energy performance. The current common architectural design process is lacking guidelines to address the impact of early design decisions in achieving the energy positive building goals. Therefore, the research is giving answer to this situation:

- Positive energy buildings require photovoltaic systems to achieve energy self-sufficiency.
- Early decisions on the building form determine the effectiveness of the photovoltaic system
- Real monitored energy data are necessary to improve the effectiveness of PV systems in positive energy buildings
- Building geometry, localization, energy performance and PV systems are key interconnected factors that are complex to manage together

- A comprehensive integrated evaluation system combining architectural design, energy parameters and solar generation technologies is required.

The current paper faces an integrated study of relevant diverse parameters for the PEB design process regarding building geometry, location, energy consumption and building integrated photovoltaics. A selection of case study office buildings provide real data for the research. The novel key performance indicators (KPIs) are designed more as relations between ratios than specific numeric values and serve as applicable knowledge for a better photovoltaic system integration in PEBs. The main contribution that synthetizes the research is a decision-making framework that can be sequentially applied, and identifies useful limits, thresholds and trends that guide the decisions for PV system integration in the early PEB design process.

Building integrated photovoltaic panels are a key technology that needs to be reasonably embedded in the design and that is producing new buildings characterized amongst other features by energy-capturing façades, extensive PV canopies and sloped roofs that face the sun. This study has focused on the office building typology that, unlike dwellings; permit a better match between energy generation and consumption due to the daytime use of the buildings.

The research proposes the integrated study of relevant diverse parameters from different fields for the PEB design process, regarding building geometry, location, energy consumption and PV system integration. A selection of case study office buildings provide real data for the research. This stage should be understood as an open database where more buildings and data could be further introduced to enrich the presented research procedure, outcome and conclusions.

The novel key performance indicators (KPIs) unveil the connection among factors from different fields, and the results of the analysis serve as applicable knowledge for a better photovoltaic system integration in PEBs. The main contribution that synthetizes the research is a decision-making framework that can be sequentially applied, and identifies useful limits, thresholds and trends that guide the decisions for PV system integration in the early PEB design process.

In order to achieve satisfactory energy self-sufficiency performance and better aesthetic, constructive and economic integration of PV in the architectural design, the decision-making framework provides a strategy to implement BIPV from the early architectural design stage of PEBs.

The main contributions of this research are:

- Definition of basic parameters for PEB design with regard to these fields: geometrical design, location, energy and PV systems.
- Selection of available and relevant office PEB case studies for a specific climatic zone, data collection, geometrical modelling and homogenization of real energy consumption data.
- Elaboration of basic ratios that combine data from the different fields that are easy to use in the analysis of PEB case studies.
- Creation of novel KPIs that elucidate relevant correlations among the basic ratios mentioned above.
- Definition of a decision-making framework for PEB architecture office design for a certain climate area, by means of novel specific KPIs with verified values and thresholds.
  - o A practical design tool to evaluate the viability of draft designs to achieve PEB goals, as in the case of architecture competitions.
  - o Easy to apply KPIs that can potentially be a requirement for PEB design and be included as pre-requisites in urban planning codes.

The conclusion can be drawn that the effectiveness of PEB design depends to a great extent on early design decisions regarding the envelope design, location etc. Several form factors such as height, envelope area and compacity tend to result in different maximization strategies, but the best balance among them is desirable. Balancing roof and façade areas is also key for a good integration of PV panels, and it should be noted that it is also possible to achieve energy self-sufficiency in locations with low irradiation if a good design is implemented. In an effort to tackle the global climate issue and to promote the decline in the use of fossil fuels, this study may be a valuable addition to the continued development of a solar design strategy that will transform the cities and architecture of the future.

The findings of this research method and the ratios between the indicators analysed could be applied to other typologies such as educational buildings and dwellings, where demands and consumptions patterns differ. Further research will be conducted including buildings of other typologies and climate conditions in order to further enrich the available database.

The proposed KPIs can have useful applications in the evaluation of different draft designs in order to determine the potential to become effective PEB designs. The given conclusions can also be implemented at the urban design scale to adjust parameters such as height, footprint and compacity ratios.

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Data availability

Data will be made available on request.

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