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Zero energy concept at neighborhood level: A case study analysis

Angeliki Mavrigiannaki[a,*], Kostas Gobakis[a], Dionysia Kolokotsa[a], Kostas Kalaitzakis[b], Anna Laura Pisello[c], Cristina Piselli[c], Marina Laskari[d], Maria Saliari[d], Margarita-Niki Assimakopoulos[d], Gloria Pignatta[e,f], Afroditi Synnefa[e], Mattheos Santamouris[e]

[a] *Technical University of Crete, School of Environmental Engineering, Chania, Greece*
[b] *Technical University of Crete, School of Electrical and Computer Engineering, Chania, Greece*
[c] *Department of Engineering, University of Perugia, Perugia, Italy*
[d] *Group of Building Environmental Studies, Physics Department, University of Athens, Athens, Greece*
[e] *School of Built Environment, Faculty of Arts, Design and Architecture, University of New South Wales (UNSW), Sydney, Australia*
[f] *Contedil di Ricco Maria and C. S.A.S., Ferrandina, Italy*

A R T I C L E I N F O

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A B S T R A C T

The concept of zero energy has emerged as the flagship for the achievement of energy conservation and CO_2 emissions reduction in the built environment. The implementation of the concept beyond single buildings offers the potential of expanding the scale of zero energy performance while overcoming the limitations of single buildings related to building use, size, on-site renewable energy availability and cost. Literature to date has discussed the zero energy concept at neighborhood scale mostly by looking at theoretical and simulated cases, including both existing and new developments. All types of energy use can be considered for achieving a zero energy balance at neighborhood scale or only the building related component. Often research focuses on Renewable Energy sizing and management for achieving the balance. The present paper analyses the real data obtained from the first year of monitoring of a pilot Zero Energy Neighborhood. A comprehensive monitoring schema, with a Web-GIS monitoring platform at its core, has been developed for the measurement and verification campaign. Performance analysis has shown that the pilot neighborhood has achieved the targets set for the net regulated consumption, renewable energy production, and cost. When considering the total consumption and PV production of the neighborhood, the first five months of monitoring starting from the beginning of summer, it has achieved a positive balance. Overall, the neighborhood has achieved a positive energy balance on a yearly basis for its regulated energy needs.

1. Introduction

In recent years, the concept of Zero Energy Buildings (ZEB) has become the flagship of efforts to achieve energy conservation and CO_2 emissions reduction in the built environment [1]. In fact, the zero energy concept is in the center of policies worldwide, being already in effect [1] , since improving the performance of buildings, ideally to zero energy levels, is vital for the accomplishment of the long-term sustainability goals [2]. Discussing the definition of the “post-carbon” city, Becchio et al. suggest that ZEBs have a key role in the de-carbonization of urban areas [3].

The transition of the concept from single buildings to building complexes offers the potential of expanding the scale of zero energy performance while overcoming the limitations of single buildings related to building use, size, on-site renewable energy availability and costs [4,5,6,7,8]. Therefore, despite lacking one shared and acknowledged definition and calculation approach [1,9,10,11,12], the zero energy concept has intrigued researchers around the globe to investigate its appli-

Abbreviations: COP, coefficient of performance; DHW, domestic hot water; DSM, demand side management; DTS, Dynamic Thermal Simulation; EER, energy efficiency ratio; EPBD, Energy Performance of Buildings Directive; GR, global radiation; HVAC, heating, ventilation and air conditioning; HVACm, HVAC monitored; HVACs, HVAC simulated; IEQ, Indoor Environmental Quality; IP, internet protocol; LCCA, Life Cycle Cost Analysis; MBE, Mean Bias Error; NZEB, nearly zero energy building; NZED, net zero energy district; ZEN, zero energy neighborhood; Positive Energy District, PED; POE, Post Occupancy Evaluation; PV, photovoltaic; R1, Residence 1; R2, Residence 2; RES, renewable energy sources; REST API, representational state transfer application programming interface; RMSE, Root Mean Square Error; Ti, indoor air temperature; TMY, typical meteorological year; To, outside air temperature; ZEB, Zero Energy Building.

* Corresponding author.
E-mail address: amavrigiannaki@isc.tuc.gr (A. Mavrigiannaki).

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cability on a bigger scale, usually the scale of a sub-section of a city [13].

In fact, studying the zero energy concept beyond single buildings is particularly relevant considering the expanding urban growth and evolving climate change that challenge cities' resilience and call for energy conservation, clean and affordable energy use [14,15]. Cities hold an undeniable potential in the transformation of the energy use landscape and as the zero energy concept presupposes the integration of renewable energy sources (RES), transposing the concept from single buildings to groups of buildings opens the potential for reaching energy self-sufficiency at the city level and may support the raise of prosumer communities [16,17].

In the following section is traced the state of the art on the zero energy concept studied at the neighborhood level.

1.1. Zero energy beyond single buildings: state of the art

In literature various terms have been used, the most common being community, neighborhood, and district, sometimes used interchangeably within the same document. The choice and use of the term are related to the perception of the spatial boundary and the interactions within the boundary. In that sense, considering the spatial boundary, a neighborhood or a district can be viewed as a sub-division of a city [6,18,19]. Effectively, representing a city miniature, a district is not merely an administrative boundary but is charged with the social, energy and cost interactions that are formed within the boundary as well as with the specific morphology that identifies it [18,19]. Similarly in [20], it is suggested that the neighborhood is a scale that integrates people and place. This view of the district or the neighborhood as a boundary of interactions approaches the notion of a community [19,20]. In fact, these interactions can influence the achievement of the zero energy goals [7].

Carlisle et al. give the definition of the net zero energy community as *"one that has greatly reduced energy needs through efficiency gains such that the balance of energy for vehicles, thermal, and electrical energy within the community is met by renewable energy"* [21]. The United States Department of Energy defines the zero-energy community as *"an energy-efficient community where, on a source energy basis, the actual annual delivered energy is less than or equal to the on-site renewable exported energy"* [22]. Amaral et al. adapt the nearly zero energy building definition of the 2010/31/EU Energy Performance of Buildings Directive (EPBD) [23] to give the nearly zero energy district definition: *"a delimited part of a city that "has a very high energy performance (…)", with the "nearly zero or very low amount of energy (…) covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby"* [19]. Considering parameters of urban density, structure and location, in order to evaluate the potential of eco-districts in becoming zero energy districts, Koutra et al. give their definition for the net zero energy district (NZED) as *"the district, where the energy supply/on-site potential is equalised by the final energy demand of its users. The NZED is "structured" and 'located' 'smartly' to ensure its long-term concept"* [24].

Location, density, and outdoor microclimate conditions of an area influence its potential to become zero energy in terms of RES integration and heating, ventilation, and air conditioning (HVAC) active performance, and consequently the design decisions for achieving this goal [6,19,25]. The results in [26] further support that layout, density and building height determine the potential of PV integration for achieving zero energy; the socio-economic status has been recognized to determine the zero energy potential as well. In the specific study, areas with organized layouts and moderate energy consumption have greater potential to reach zero energy compared to suburban affluent neighborhoods with high energy use intensity. In addition, the size of the investigated energy communities plays a key role in determining their efficiency and sustainability. That is the reason why further investigation about optimal sizing is also carried out, with varying climate context and other boundary conditions [27].

Both existing areas [6,7,28,16,18,26,29,30,31,32,33,34], as well as new developments [28,27,35,36,37,38,39,40,41,42,43,44], have been studied for their potential to become zero energy. A few researchers consider a holistic approach to the energy balance of the district, introducing all types of energy uses in the discussion (buildings, transportation, industry, public spaces) [6,18,19,21,24,29]. Most studies investigate zero energy communities focusing on the building-related energy component, either comprising various types of buildings [35,36,37,30,32,42,44,45,46], or only residential [7,28,16,26,27,47,33,34,38,40,41,43]. The size can vary from a few residential buildings, to tens, hundreds or more than thousand, in areas with urban or suburban character and in a few cases rural areas.

Moreover, research is driven by the consideration that renewables – most commonly solar energy – are integral to the zero energy concept and investigate relevant implications related to RES planning, sizing, costs, mismatch management and effects on the grid [36,47,31,32,39,41,43,45,46,48,49]. Lopes et al. simulated a hypothetical community of five residential buildings and demonstrated that demand-side management can improve load matching when applied at the community level, as opposed to single ZEBs, owing to more control points being available and higher energy production at the community level [47].

Performance targets are presented scarcely and they are defined in relation to the research scope. In [36], 44.7 kWh/m^2/y regulated energy demand of energy plus houses is considered for sizing a district heating and renewable energy system for a mixed-use net zero energy community in South Korea. The performance target of two near zero energy home communities in California was set for achieving 50–60% energy cost reduction compared to a home built to code. The houses' measured performance showed >70% cooling energy use reduction compared to buildings built to code [40]. The measured average energy consumption (April-December 2013) of the net zero energy development West Village in California was 3.1 kWh/m^2/month regulated energy use and 5.8 kWh/m^2/month total energy use [50]. In [39], 80% of the primary energy needs are met by renewable energy sources, according to simulation results, and in [29], up to 91% global energy consumption reduction is calculated that can be achieved when transforming neighborhoods to become zero energy, depending on the retrofit scenario chosen.

Ascione et al. [37] designed and evaluated the potential of a zero energy settlement in Greece. The settlement is a holiday village, composed of residences, hotels, and commercial buildings. Simulation results showed that buildings with low energy demand, like residences, were more likely to achieve zero energy compared to high energy demand buildings, like hotels. It could be concluded that the combination of building types and uses would favor the achievement of zero energy settlements. Besides, considering the totality of the energy needs – building, transportation, public spaces – a zero energy district is not composed of zero energy buildings, but rather by buildings of varying energy performance levels that along with the public space and transportation needs, reach a near zero balance [19].

Investigating the potential of a solar community to become zero energy, Hachem-Vermette et al. conclude that 70% of total energy consumption can be covered by PV generation, 90% of thermal consumption can be covered by solar thermal and combination of PV, solar thermal and thermal storage results in a positive energy community [35]. The economically viable options for reaching positive energy communities are limited, according to simulation results for a positive energy community in Greece, and would require advances in the minimum insulation levels currently prescribed in the National Regulation [28].

In terms of costs, Lu et al. performed an investigation of the economic performance of a net zero energy community with PV installation under a reward-penalty mechanism, the mechanism favored the higher levels of RES inclusion towards the achievement of the net zero energy status [33]. A cost-benefit analysis accounting for multiple co-impacts and using the social return on investment index is presented by Becchio et al. with the aim to support decision making for retrofitting existing districts to become net zero energy [34]. Kalaycıoğlu and Yılmaz implemented the EU cost-optimal methodology to study the cost-optimal solutions for zero energy districts. The authors also calculated the investment cost of a zero energy building to be 40% higher than a reference building [44]. The capital costs for building retrofit to near zero energy building (NZEB) levels have been calculated to be 198% higher than the business as usual retrofit while using a neighborhood approach to NZEB retrofit the capital costs are reduced by 16.8% compared to capital costs for single NZEB retrofit [28].

Moving forward, the term Green Neighborhoods is also used. This term aligned with the European Green Deal [51], is a set of buildings over a delimited area, at a scale that is smaller than a district, with potential synergies, in particular in the area of energy [52]. A green neighborhood is a neighborhood that allows for environmentally friendly, sustainable patterns and behaviors to flourish (e.g. bioclimatic architecture, renewable energy, soft and zero-emission mobility etc.). Green neighborhoods are the building blocks of Positive Energy Districts (PEDs) by implementing key elements of PED energy systems [53,54]. For example, the exchange of energy between buildings increases the share of local self-supply with climate-neutral energy and system efficiency.

1.2. Zero energy performance monitoring

Monitoring is indispensable for tracking and effectively improving the implementation of the zero energy concept [4,11,55,56,57,50]. When enhancing building energy performance, the human and the occupancy pattern components may result in a great difference between predicted and effectively consumed energy, since building operation may lead to unpredictable building use and HVAC operation [30,50,58,59]. For that reason, a key scientific effort is aimed at demonstrating the importance of real monitored data for identifying and reducing the energy performance gap [60,61]. The availability of real data from monitoring allows for a sound assessment of the performance gap [60]. Besides, smart monitoring combined with building energy management and predictive controls contribute to zero energy performance and can be further utilized towards maintaining or advancing building performance [60,62].

In the zero energy communities' state of the art, research in discussing simulation results is more widespread than research on measured performance results. In [40], results from the measured power consumption of two near zero energy home communities in California are presented. The focus is on percentage reduction of cooling electricity demand, peak electricity demand and electricity bills compared to houses built to code. In [50], monitoring and verification of performance were intended in identifying the gap compared to design and modeling assumptions. Measured results of nine months revealed that measured energy performance was 15% higher than expected from simulations and an occupant engagement campaign followed with the aim to drive energy conservation. Similarly in [30], measured performance results of community zero energy retrofit projects are discussed. The residential retrofit project had higher energy consumption than what was expected from the simulation, which was linked to occupant behavior. An intervention followed for raising occupant awareness on appropriate HVAC use and ventilation principles. A campus retrofit project that included three college buildings, had measured energy consumption close to what was expected from simulations, however, the occupant thermal comfort was rated lower than pre-retrofit [30]. Finally, in [42], one year's worth of measured performance results showed the achievement of a 134.5% net-plus energy community in an eco-friendly energy town composed of six public buildings and a hybrid renewable energy system.

1.3. Contribution of the present research

The transition of focus from single ZEBs to zero energy neighborhoods for a multifaceted (economic, environmental, energy) successful implementation of the zero energy aspiration is the subject of this paper. Realized examples and measured performance results are necessary for the proof of concept. The basis for this paper is a real case study that has been designed and constructed to be a zero energy neighborhood (ZEN).

The definition of the zero energy boundary and consequently of the zero energy balance has been thoroughly discussed in the literature for single ZEBs, still with no concrete and commonly accepted approach [1,9,10,11]. Consequently, this ambiguity is transferred to the neighborhood scale [12]. At neighborhood scale, extra considerations can be entered, such as the inclusion of all types of energy in the balance [21], as well as neighborhood characteristics that contribute to or hinder the balance [24].

In this paper, the case study is composed of high-energy performance residential buildings and on site RES. Therefore, the case study is a "site renewable energy" neighborhood that its RES production aims to balance its energy needs. Specifically, the ZEN has the following performance targets:

Net regulated energy consumption at building level ≤ 20 kWh/m^2/year;
Regulated energy consumption at building level ≤ 70 kWh/m^2/year;
Renewable energy production at neighborhood level ≥ 50 kWh/m^2/year;
Investment cost reduction per building ≥ 16% compared to costs for a single ZEB of similar performance.

Where:

Regulated energy use = heating, cooling, domestic hot water, fans, pumps and ventilation.

Renewable energy = energy production from building-integrated renewables and energy production by the neighborhood renewables.

Net regulated energy = Regulated energy use - Renewable energy.

2. Methodology

2.1. Neighborhood overview

The pilot neighborhood is part of a housing development area currently under construction in Granarolo dell'Emilia, in Emilia-Romagna, Italy. The development location is characterized by temperate and Mediterranean climate, with 2162 heating degree-days and 110 cooling degree-days.

Within the development, an area of approximately 2,760 m^2 has been constructed to demonstrate the ZEN concept that includes two single-family houses: one single-story residence and one two-story residence and the surrounding external area (Fig. 1). Six more residences are planned to be built in the development. The ultimate intention is to build the entire development following the pilot ZEN concept with the aim to improve the energy efficiency, the microclimate conditions, and the livability of the entire area.

The gross floor area of each residence is approximately 250 m^2. Each residence is designed to host one family of up to five people. Two families moved into the residences after construction was completed, in summer 2018 and spring 2019, respectively. The main as-built characteristics of the two residences are summarized in Table 1.

The buildings' HVAC system consists of an air-to-water heat pump with 8kWcapacity, coefficient of performance (COP) equal to 4.1 and an energy efficiency ratio (EER) equal to 3.8, a digital control for thermoregulation and mechanical ventilation with heat recovery (70% efficiency). The heat pump is connected to a low-temperature under floor heating system. Fig. 2 shows the schematic of the HVAC system inside the buildings.

The ZEN includes a set of microclimate mitigation techniques, renewable energy production, energy conservation, and energy management technologies, as follows:

- Dedicated greenery for local overheating mitigation [63];
- XPS insulation for energy conservation;

Table 1
As-built characteristics of the residences.

Size	Residence 1 (R1)	Residence 2 (R2)
Total floor area	259 m^2	241 m^2
Net floor area	131 m^2	118 m^2
Orientation	North-West	North-West
Stories	2	1
Bedrooms	3	3
Fabric		
Wall U-value*	0.250 W/m^2K	0.164 W/m^2K
Roof U-value	0.117 W/m^2K	0.117 W/m^2K
Floor U-value	0.167 W/m^2K	0.167 W/m^2K
Window Ug	0.600 W/m^2K	0.600 W/m^2K
Glazing	Low-e triple glazing with argon-filled cavities	
Window shading	Manual blinds	

*Measured U-value post-construction.

Fig. 1. The residences in the pilot ZEN (top) and the development under construction in the background (bottom).

- PV polycrystalline panels 12 kWp for renewable energy production (6kWp on each rooftop);
- Energy storage system: 200 V Li-Ion battery with 4 kWh storage capacity (one battery in each residence with the possibility to increase capacity up to 12 kWh and characterized by a 95% deep discharge, 1.6 kW charge power, and 2kW discharge power) associated with a 3.6 kW hybrid inverter (used to convert the direct current power generated by the PV panels to alternating current power for self-consumption and vice versa to allow the battery to store electricity as DC power), and control platform with dedicated mobile app;
- Load Control system for load management;
- Home Energy Management System, for building energy management.

The selection and size of the technologies is the result of optimized design for achieving simultaneously the targets of renewable energy production, regulated energy consumption, and investment cost reduction [64].

The PV panels are located on the rooftops of the residences (Fig. 3) and the two energy storage systems (battery and inverter) are installed in the garages of the respective residence. The energy produced by the PVs is used in the following order:

1. PV energy production is directly used to cover the neighborhood's (buildings + external lighting) electricity needs.
2. Excess production is stored.
3. Further excess is exported to the grid.

The PV production target is calculated as follows:

Total PV production in the year / Sum of residences net floor area ≥ 50 kWh/m^2*/year*

At the time of design and construction and during the first year of monitoring, the concept of shared energy communities had not been enacted yet by Italian regulations; independent energy contracts related to energy community only were not allowed in Italy. That is the reason why the project fostered the implementation of a third only-energy user that is entitled to produce and monitor stored electric energy. Since the electric grid has been acquired by a third owner in charge of the project, both the houses' owners can manage independently their renewable system linked to individual batteries. Each building consumes only the PV production by the panels located on its rooftop and stores excess production on the respective building battery.

For the present analysis, it is assumed that PV production and storage are shared, meaning that the total PV production from the two PV rooftop installations is calculated as the aggregated neighborhood production that is available to cover the aggregated energy demand of the neighborhood. Similarly, the stored energy from the batteries is assumed to be the aggregated stored energy at neighborhood level. At the moment, energy communities are allowed in Italy as well, meaning that this example represents what should be implemented in a real shared system where the owners take part to the community grid and facilities, and can produce-buy-sell-counter energy needs and excess power.

2.2. Zero energy neighborhood design and construction

The achievement of optimized energy and cost-efficient solutions for zero energy neighborhoods requires an integrated, holistic approach to design and simulation [65]. Furthermore, energy design and optimization beyond single buildings can be optimally planned and managed through integrated energy master planning including multiple stakeholders and continuous iterations [12,66]. An integrated approach to design, construction and monitoring has been developed and implemented for the case study (Fig. 4) with the aim to achieve the specific energy and cost targets.

At the design stage Dynamic Thermal Simulation (DTS) tools have been employed for energy performance simulation and optimization. First, building performance has been optimized through established energy conservation and efficiency design strategies and technologies.

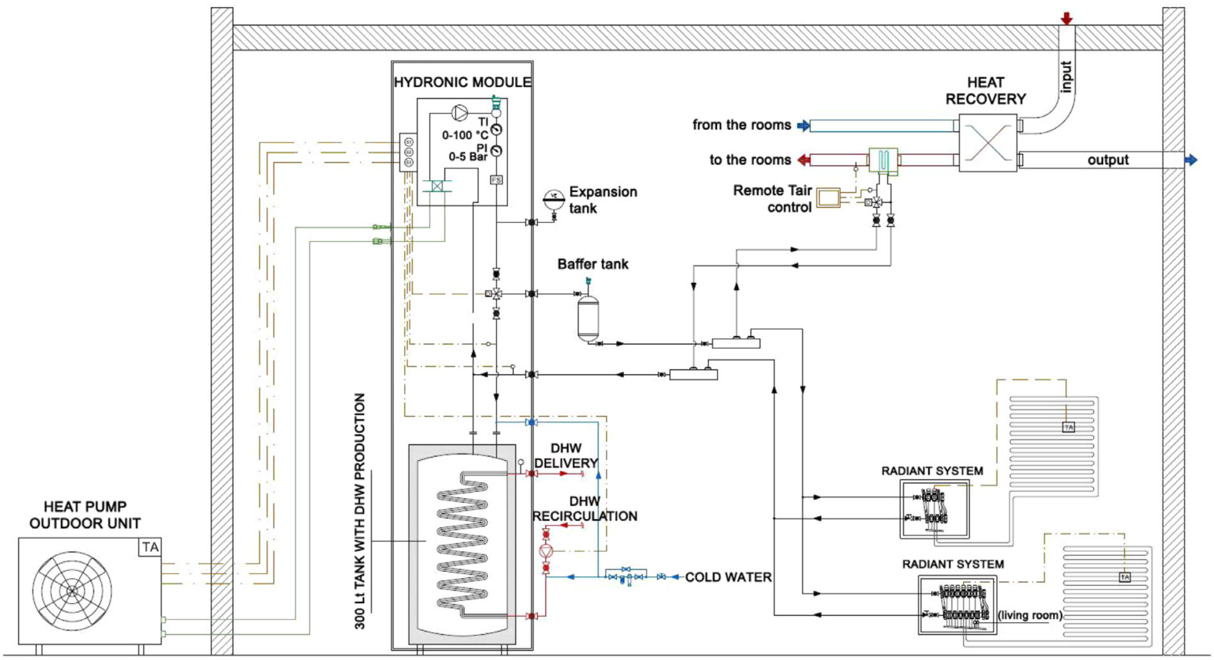

Fig. 2. schematic of the HVAC system inside the buildings.

Fig. 3. PV panels on the rooftops of the residences.

Next, advanced energy conservation, energy generation and energy storage technologies are selected and simulated, separately as well as packages integrated with building simulations [67]. In addition, microclimate simulations serve the determination of performance under alternative microclimate scenarios [25]. At the end of the design stage, the final selection and size of the technologies (energy conservation, energy generation and storage) is the result of optimisation for achieving simultaneously the targets of renewable energy production, regulated energy consumption, and investment cost reduction. Life Cycle Cost Analysis (LCCA) aims to minimize costs while respecting the energy performance constraints [64], leading to the optimized design of energy and costs. A Cost Control Tool and a Change Management Tool have been developed for tracking alterations to design during construction and consequently track possible changes in the performance targets [68]. Thus, after completion of construction and installation, pre-occupancy checks along with pre-occupancy monitoring serve the checking of simultaneous performance of the buildings and technologies prior to occupants' move-in while the results feed the calibration of the design simulation models for obtaining the as-built simulated performance. Continuous monitoring during occupancy supports the measurement and verification of energy consumption and energy production as well as the indoor environmental quality and ultimately evaluation of the performance targets. The monitored data are collected, stored and visualized on a Web-GIS platform. In addition, Post Occupancy Evaluation (POE) surveys evaluate the occupants' satisfaction and their interaction with the buildings and installed technologies. POE results and collection of actual performance data allow the updated calibration of the simulation models for performance evaluation and assessment of the performance gap at the end of one year of monitoring.

2.2.1. Simulated performance

The expected performance – heating, cooling, mechanical ventilation, domestic hot water (DHW), equipment, lighting consumption and PV production – of the pilot neighborhood is simulated with the EnergyPlus dynamic simulation engine [69]. The graphical interface of DesignBuilder has been used for modeling. A single model is developed including the two buildings and the energy production systems of the neighborhood, namely building integrated and shared PVs. The buildings are modeled in detail by considering all passive and active technologies. The typical meteorological year (TMY) for the specific case study location, i.e. Granarolo dell'Emilia, Bologna, Italy, has been developed using climate input data from the software Meteonorm [70].

After completion of construction and commissioning, on-site pre-occupancy checks and pre-occupancy monitoring have been performed prior to residents entering the buildings [71]. Pre-occupancy checks and monitoring intend to provide a baseline performance according to the as-built conditions and include:

- Building diagnostics (U-value, air permeability)
- Systems & technologies performance check
- Monitoring system quality check

The pre-occupancy data have been used for a first calibration of the simulation models in free-running conditions. The purpose of the calibration is to simulate the expected performance according to the as-built status of the buildings and the installed technologies, i.e. the "as-built" performance. The expected performance of the pilot ZEN, according to the "as-built" simulations is given in Table 2.

A second calibration is performed after one complete year of monitoring to reflect actual conditions of operation, i.e. including systems performance and occupant behavior. Occupancy and occupant-building

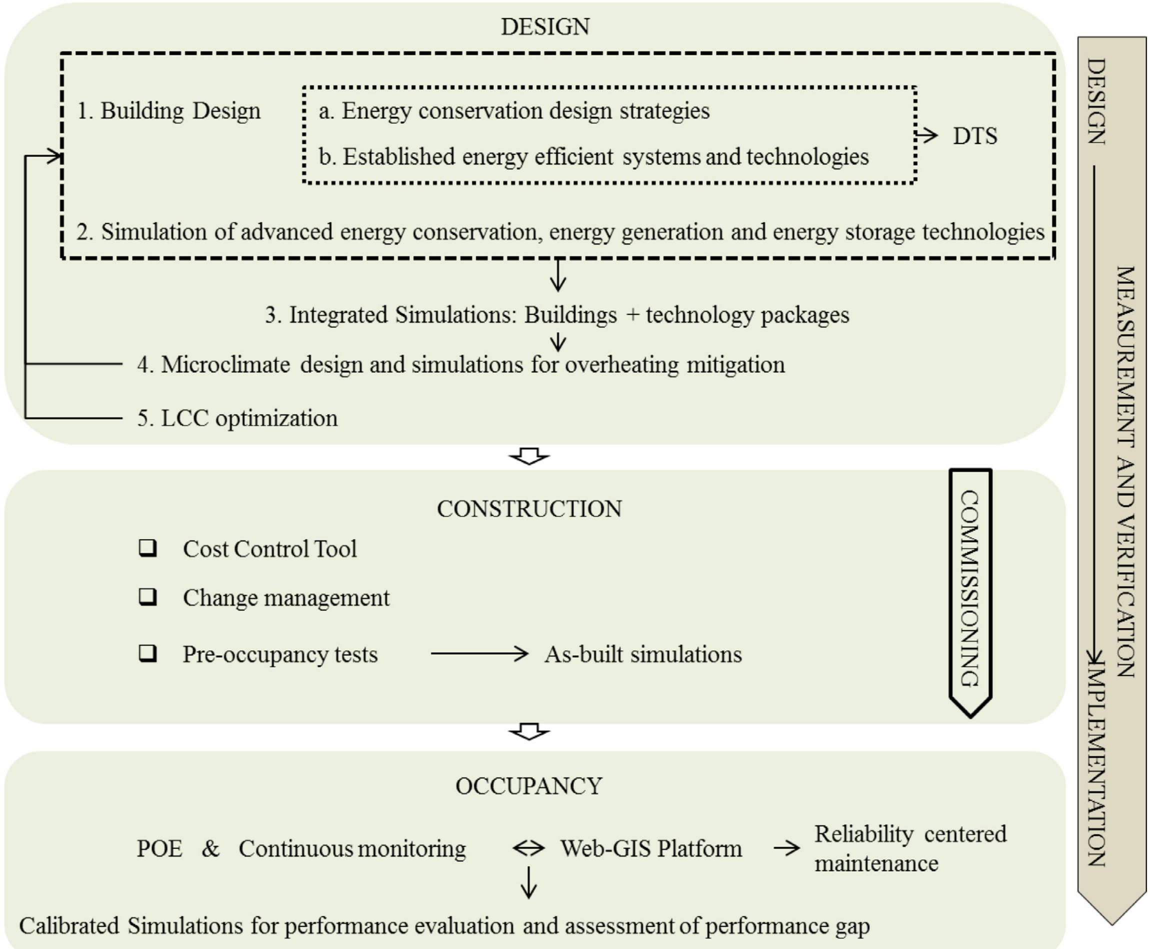

Fig. 4. Design and Construction process for a zero energy neighborhood.

Table 2
As-built simulated performance of the pilot ZEN.

$kWh/m^2/y$	Design targets	Residence 1	Residence 2
		Expected performance from “as-built” simulations	
Regulated energy use	<70	47.4	47.5
Renewable energy	>50	49.7	49.7
Net regulated energy	<20	-2.3	-2.2

Table 3
Details of the two stages of calibrations for the simulated performance of the pilot ZEN.

	First calibration		Second Calibration	
When	After completion of pre-occupancy checks and pre-occupancy monitoring		After one complete year of post-occupancy monitoring	
Adjustments	U-values of external walls		HVAC Set-points and set-backs	
	Air-permeability from blower door test		Occupants presence schedules	
	As-built design modifications (mainly in terms of windows and shutters)		Occupants building systems operation schedules	
Target parameter	Indoor air temperature		Energy consumption	
Calibration period	R1: June 19th - July 6th 2018		June 2019 - March 2020	
	R2: February 1st - march 5th 2019			
Indexes	**MBE**	**RMSE**	**NMBE**	**CV(RMSE)**
R1	-0.06°C	0.57°C	-0.26%	6.36%
R2	-0.09°C	0.84°C	-2.53%	8.15%

interaction, different for the two buildings, have been modeled according to the insights from the POE and monitoring [71].The details of the two stages of calibrations are given in Table 3.

Two validation indices have been used to quantify the model accuracy for each calibration stage. Mean Bias Error (MBE) and Root Mean Square Error (RMSE) have been calculated in the first calibration stage (as-built). The calculation of the indices is defined in Eq. 1 for MBE and Eq. 2 for RMSE.

$$MBE = \frac{\sum_{i=1}^{n} (M_i - S_i)}{n} \; [°C] \tag{1}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (M_i - S_i)^2}{n}} \; [°C] \tag{2}$$

Where S are the simulated values and M are the measured values.

According to the validation criteria specified in the ASHRAE Guideline14 [72], the reference tolerance values correspond to ±0.5°C for MBE and to 1°C for RMSE, considering sub-hourly temperature values.

Calculation of normalized MBE (NMBE) and coefficient of variation of the RMSE (CV(RMSE)) has been performed for the second calibration stage, as defined in Eq. 3 and Eq. 4 respectively.

$$\boldsymbol{NMBE} = \frac{\sum_{i=1}^{n} \left(\boldsymbol{M}_i - \boldsymbol{S}_i\right)}{(\boldsymbol{n}-1)\,\bar{\boldsymbol{M}}} \times 100\ [\%] \tag{3}$$

$$\boldsymbol{CV}(\boldsymbol{RMSE}) = \frac{1}{\bar{\boldsymbol{M}}}\sqrt{\frac{\sum_{i=1}^{n} \left(\boldsymbol{M}_i - \boldsymbol{S}_i\right)^2}{(\boldsymbol{n}-1)}} \times 100\ [\%] \tag{4}$$

According to the validation criteria specified in the ASHRAE Guideline14 [72] the simulation model can be considered calibrated with NMBE < 5% and CV(RMSE) < 15%, considering monthly energy consumption values.

2.3. Monitoring

For effective monitoring of the ZEN performance, a specifically designed measurement and verification process has been developed and implemented. The measurement and verification are integrated into an iterative project management flow, incorporating technical guidance from established measurement and verification protocols and governed by quality control. Quality control is intended to ensure the collection of quality data and build confidence in the monitored performance results [73].

A Web-GIS platform has been created in order to support monitoring and, by extension, performance measurement and verification. The Web-GIS platform is the core component of the neighborhood's monitoring scheme, where all the information from the various sources (sensors inside rooms, energy monitoring of RES, weather station etc.) is gathered, stored, analyzed and presented to the users [74].

A graphical representation of the data collection schema for the ZEN is given in Fig. 5. The monitoring devices for IEQ (Fig. 6) and building energy consumption (Fig. 7) transmit the measurements via Ethernet to a KNX router. The KNX router gathers and transmits the measurements to the Web-GIS platform via a REST API [75]. The HVAC set-point is transmitted to the HVAC manufacturer's cloud platform and the Web-GIS platform reads the set-point from the manufacturers' website. The PV production and storage data are collected on the inverter and recorded on the inverter provider's platform; the data are then transmitted between the platforms via REST API communication. The weather station communicates wirelessly with the platform. All collected data are transmitted in near real-time to the Web-GIS platform and the sampling time is 15 minutes.

2.3.1. Collection of quality data

Data quality criteria can vary depending on the type of data collected and the purpose of data collection [76,77,78,79]. In the studied case, the purpose of data collection is the actual performance evaluation; therefore, data collection has been designed according to this purpose. Reviewing the many criteria and various data quality assessment methodologies Batini et al. note that the most commonly used criteria are: accuracy, completeness, consistency, and timeliness [76]. In fact, accuracy and completeness have been identified as the main reasons for compromised data quality [80]. The collected data are numerical values, so interest is in collecting correct values (accuracy), in the number of missing values (completeness), in eliminating duplicate entries (uniqueness), and finally in collecting data with the correct timestamp (timeliness). Therefore, the quality of the collected data has been designed and assessed according to the above-mentioned criteria.

The steps towards quality data collection (Fig. 8) include:

- Decisions in the planning and design phase by setting the monitoring equipment specifications, including monitoring equipment placement (accuracy);
- Quality control throughout the planning, installation and use of the monitoring schema (uniqueness, timeliness, completeness).

2.4. Measured performance evaluation

The present paper focuses on the analysis of the first year of monitored performance data obtained from a pilot neighborhood that has been designed and constructed to be a ZEN. The first results from the actual performance of the pilot neighborhood, covering one-year period, are evaluated. The aim of performance evaluation is the identification of a possible performance gap, the validation of the performance targets and the assessment of the zero energy balance.

2.4.1. Actual performance against simulated performance

First, the actual performance data are compared against the expected performance that resulted from the simulation models after their calibration according to the as-built conditions. This comparison intends to reveal agreement or deviations between the expected and actual performance and consequently provide insight on the occupants' contribution to the performance gap.

At this stage, the energy signature is used as a tool to support the energy performance evaluation and the investigation of differences. The building energy signature is a qualitative method of assessing the energy performance of buildings [81]. It can be used as a reference and an indication of the expected consumption as well as for identifying and interpreting possible changes [82]. Therefore, defining and studying the energy signature can offer a primary tool of energy performance evaluation throughout a building's lifetime.

In principle, the energy signature is a correlation of a building's heating and cooling energy use with climatic variables, usually the external air temperature. The graphical representation of the energy signature is given with a scatter plot. The slope of the signature indicates the HVAC consumption sensitivity to the external temperature. The slope can also be interpreted as the building's heat loss coefficient [81,83,84,85]. Vertical shifts of the signature indicate changes in the HVAC system such as a system upgrade [81].

The energy signature can convey different information depending on the data resolution level; the use of hourly data reveals information that are hidden when daily data are used [86]. The identification of energy trends throughout the years can be achieved with the use of daily data. However dynamic trends, such as peaks, require the use of hourly data or even sub-hourly data, depending on the available measurements. In the present work, hourly data have been used for building and comparing the energy signatures of actual performance against simulated performance. This approach supports the investigation of the performance gap and its relation to HVAC operation.

2.4.2. Actual performance compared to design performance targets

The case study design has been led by specific performance targets and an integrated approach has been developed and implemented with the aim to achieve these performance targets. Therefore, in the next step the measured performance of the first year is compared to the design performance targets.

2.4.3. Zero energy balance

The case study is a “site renewable energy” neighborhood currently composed of residential buildings and PV RES. Furthermore, its design performance targets focus on regulated energy and RES production. Therefore, the balance is assessed considering the balance between RES production and regulated residential consumption. In addition, considering that most existing definitions of zero energy neighborhoods in literature account the total (regulated + unregulated) energy needs of the

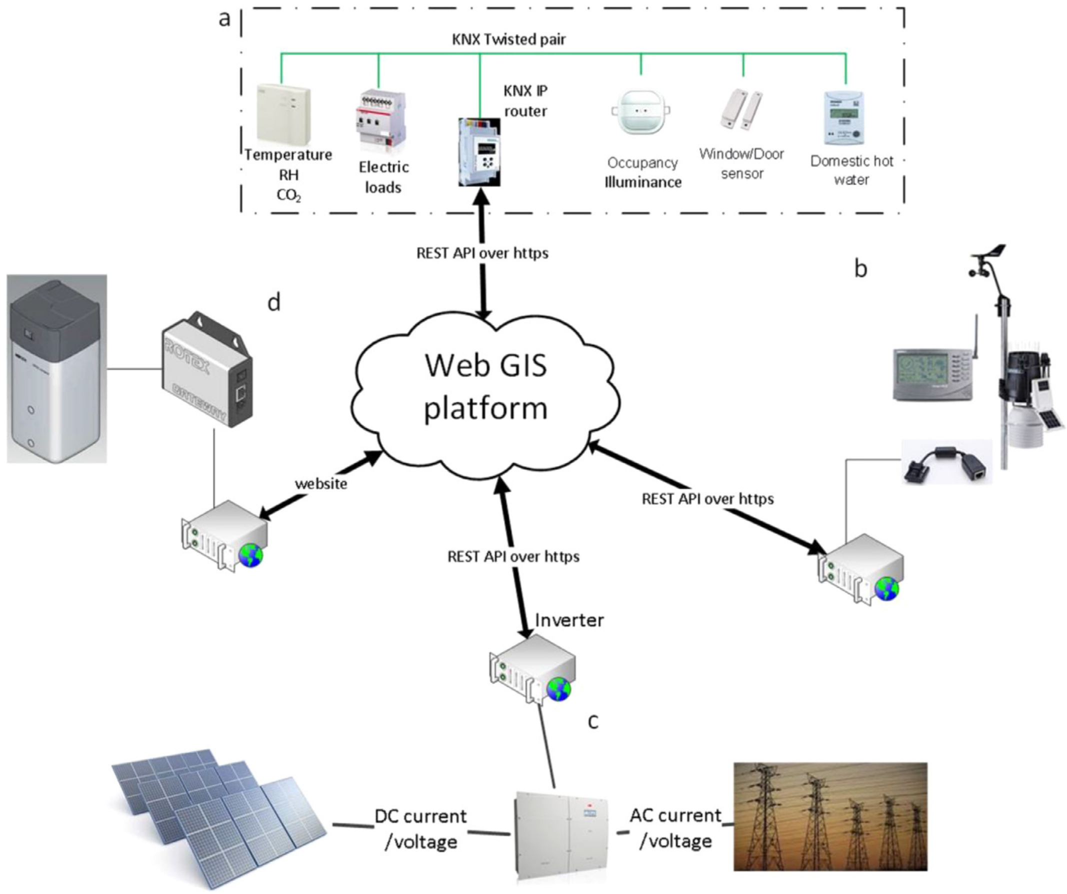

Fig. 5. The data collection schema: a) The IEQ and building energy consumption monitoring devices, b) The weather station, c) PV, energy storage and national grid electricity monitoring, d) HVAC set-point monitoring. The Web-GIS platform is in the center.

Fig. 6. a) Presence sensor, b) Air quality sensor, c) HVAC thermostat.

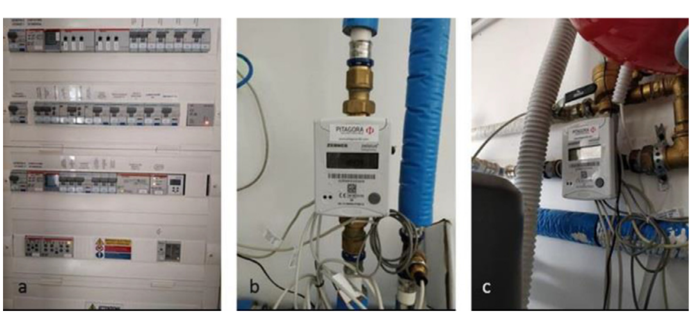

Fig. 7. a) Electricity metering, b) Heat pump energy meter, c) DHW meter.

buildings in the balance calculation, the balance between the total measured consumption and RES production is also assessed. This approach is similar to the load/generation balance discussed in [11].

The usual period of balance in literature is the year basis. Here an evaluation of both the year as well as the monthly basis is presented.

The following indicators are calculated for evaluating the zero energy balance:

PV production/Total consumption (%)
PV production/Regulated Consumption (%)
Direct Self-Consumption/PV Production (%)
Self-Consumption/PV Production (%)
Self-Consumption/ Total Consumption (%)
Self-Consumption/ Regulated Consumption (%)

The Direct Self-consumption is the amount of the PV consumption that is directly consumed in the neighborhood.

3. Measured performance results

3.1. Actual performance against simulated performance

The monitored HVAC performance against the expected HVAC performance per month is presented in Fig. 9 and Fig. 10, for *R1* and *R2* respectively. The differences in kWh/m^2 and % per month as well as for the whole year are given in Table 4. In both houses, differences in consumption between the expected and actual values are observed. In *R1*, the monitored total HVAC consumption (R1HVACm) is -2% lower than the simulated (R1HVACs), but the performance difference per month ranges from –9% in March 2020 to 565% in May 2020. In *R2*, the monitored total HVAC consumption (R2HVACm) is higher than the simulated (R2HVACs) by 65%, the performance difference per month ranges from 19% in July 2019 to 393% in September 2019. The biggest percentage differences are observed in the intermediate season months for both houses. Especially for the spring of 2020, the differences can be related

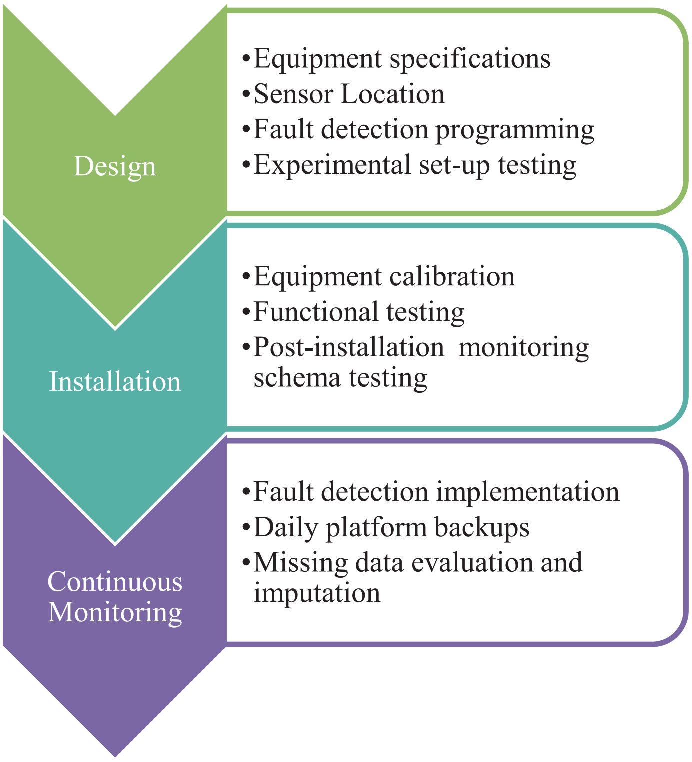

Fig. 8. Steps towards quality data collection through the monitoring schema.

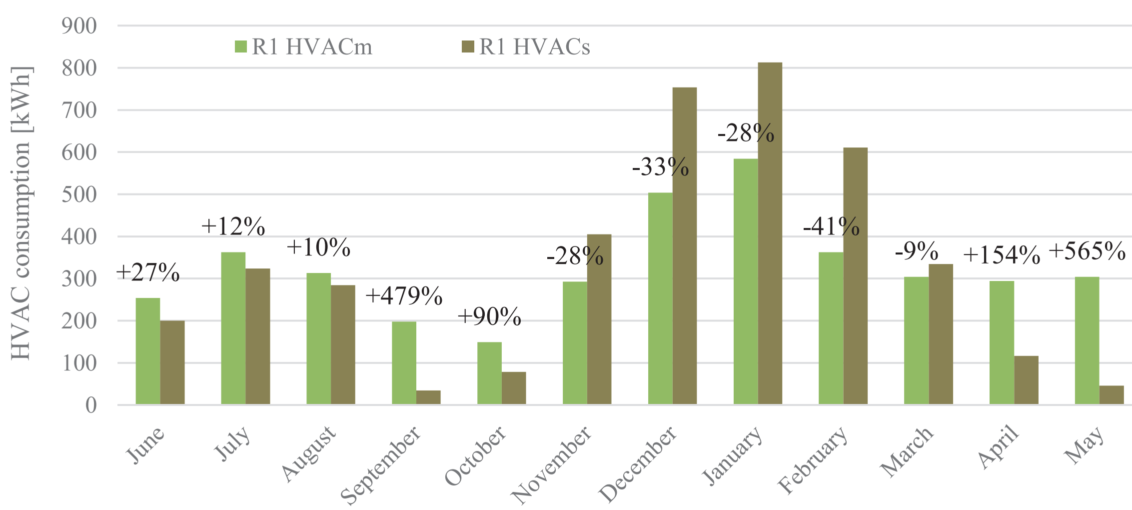

Fig. 9. Monitored (R1HVACm) and simulated (R1HVACs) HVAC consumption of Residence 1, per month for the period of June 2019 – May 2020.

to the COVID19 lockdown and continuous presence of occupants in the houses.

The energy signatures in Fig. 11 and Fig. 12 provide further insight on the differences. In the heating season, the HVAC consumption trend is similar to that from the as-built simulations for both residences (Fig. 11 and Fig. 12). However, in R2, the monitored HVAC consumption (R2HVACm) is higher than the simulated one (R2HVACs), which is indicated by the shift of the signature (Fig. 12). During the cooling season, the monitored data are less dispersed compared to the simulation results in both residences and the slope of the energy signature is less inclined. Since the signature slope gives information on the sensitivity of the air conditioning system to the outdoor dry-bulb temperature, it appears that the outdoor environmental conditions are not among the most significant values affecting occupants' operation of the cooling system. The energy performance gap seems to be partly associated with the different actual building end-use compared to the expected behavior [59]. At the design stage, indeed, standard occupant behavior schedules [87] were used in dynamic building simulation, since the real occupancy and HVAC operation pattern was unknown. Therefore, the observed differences between seasons as well as between the two houses, indicate that actual HVAC consumption is dependent on actual occupant behavior.

In fact, the analysis of monitored indoor thermal conditions during the cooling season revealed a trend of small fluctuations in room air temperatures throughout the day (Fig. 13 and Fig. 14). The occupants tend to leave the HVAC system continuously on even in early autumn (cooling period) when it was assumed to be mostly off. In addition the occupants operate the system on a tight set point, whereas in the simulations the system was assumed to be operated with set point and setback temperatures adjusted for heating and cooling period. As a result, the system,

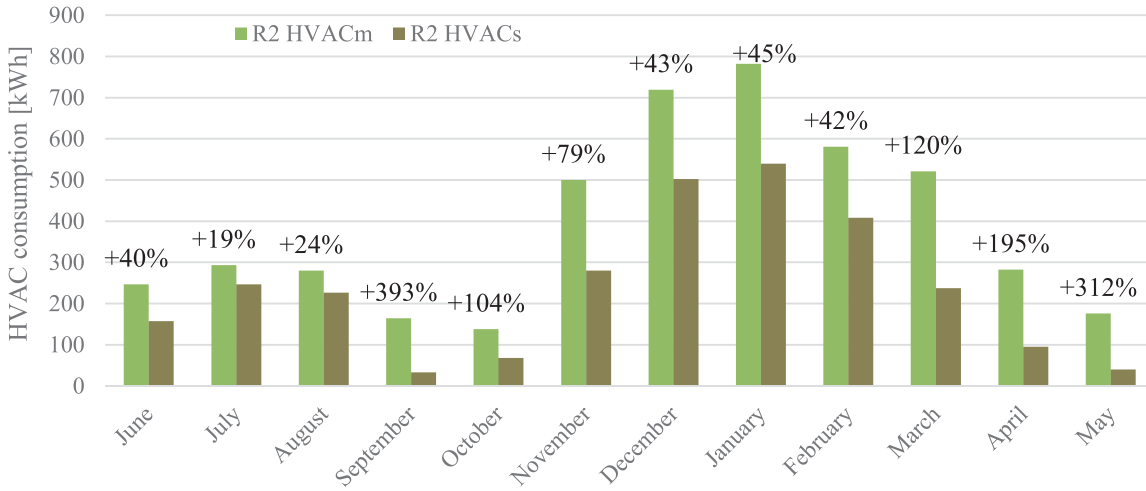

Fig. 10. Monitored (R2HVACm) and simulated (R2HVACs) HVAC consumption of Residence 2, per month for the period of June 2019 – May 2020.

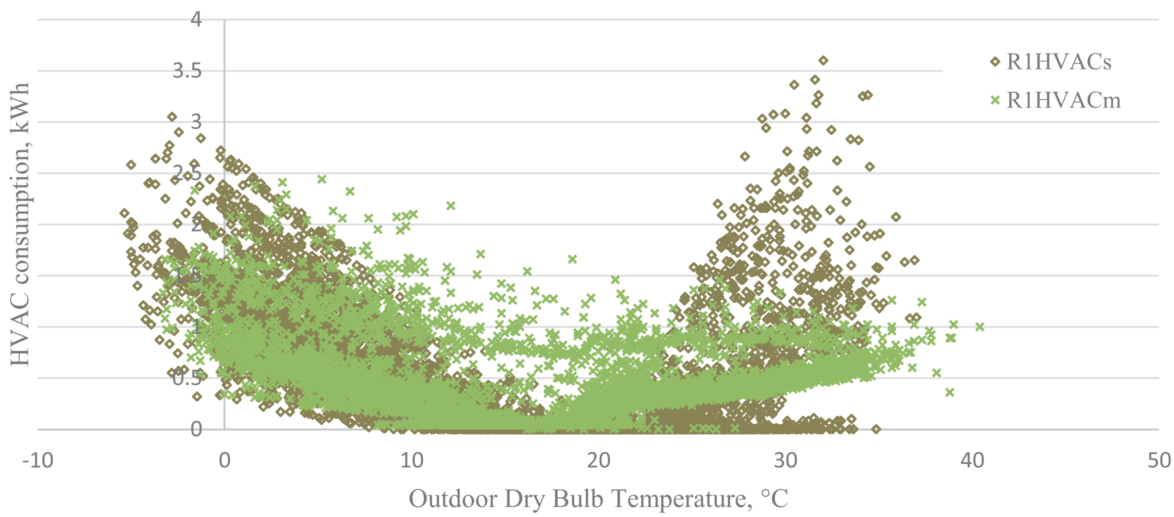

Fig. 11. Residence 1 Energy Signature, hourly data, simulated (R1HVACs) vs monitored (R1HVACm).

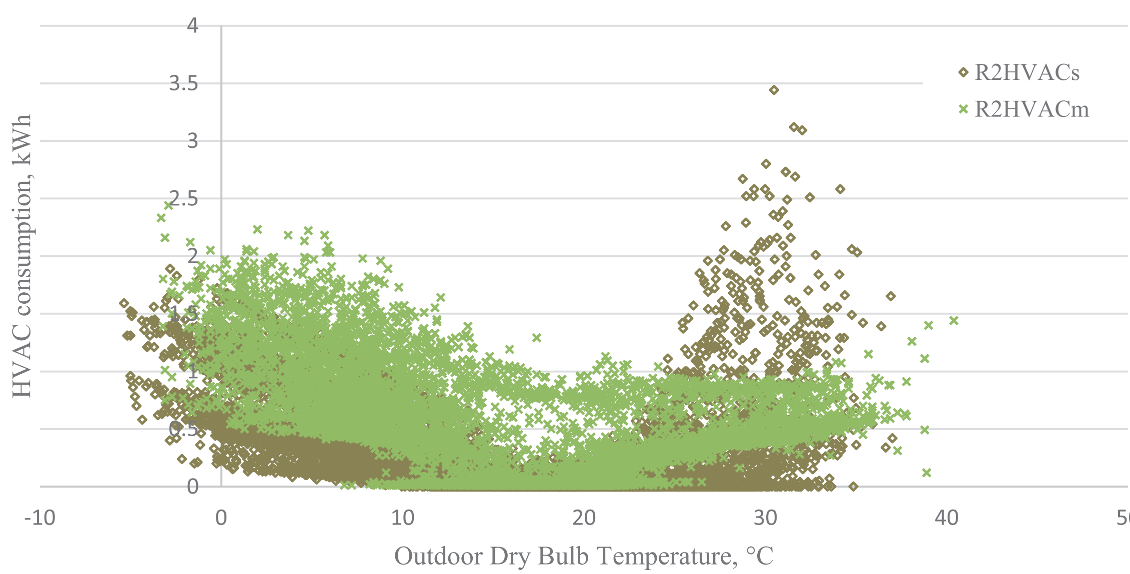

Fig. 12. Residence 2 Energy Signature, hourly data, simulated (R2HVACs) vs monitored (R2HVACm).

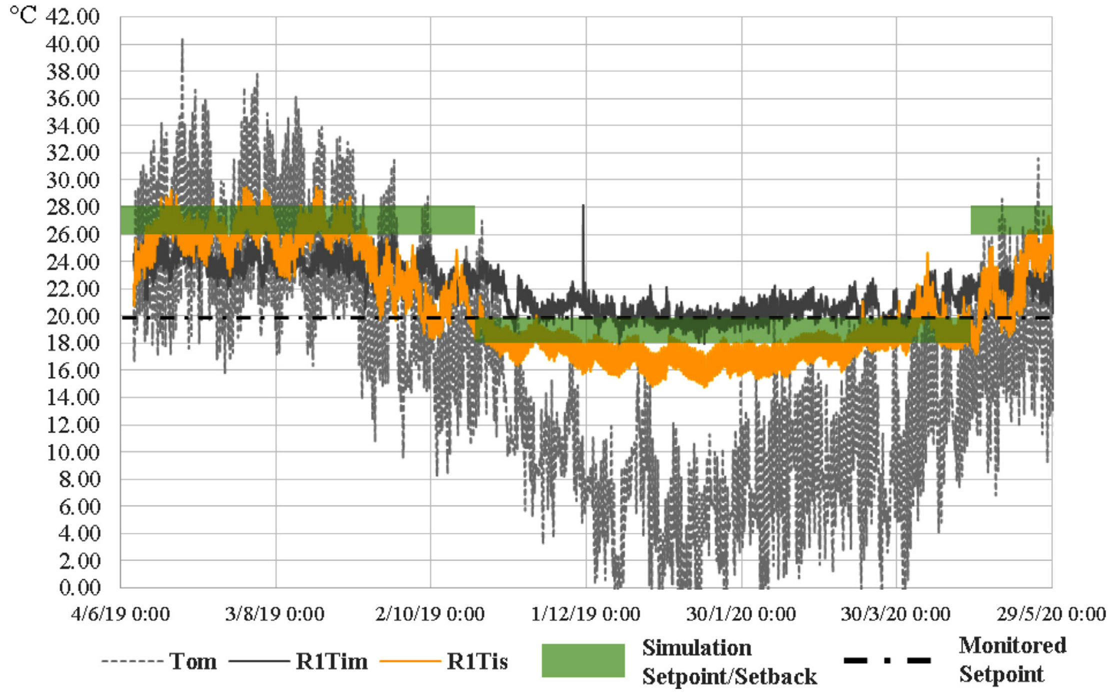

Fig. 13. Indoor temperature of Residence 1 according to monitored data (R1Tim) and simulations (R1Tis), along with set-point/setback assumptions for simulations and actual set point during occupancy; hourly data for the period of June 2019 – May 2020.

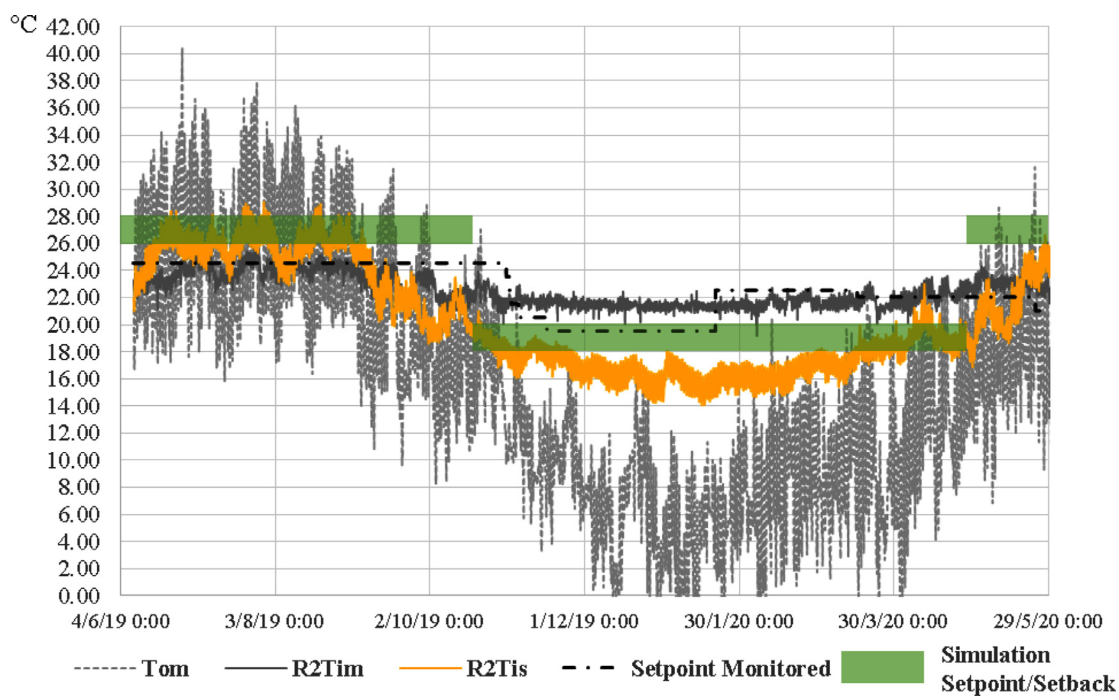

Fig. 14. Indoor temperature of Residence 2 according to monitored data (R2Tim) and simulations (R2Tis), along with set-point/setback assumptions for simulations and actual set point during occupancy; hourly data for the period of June 2019 – May 2020.

as assumed in the simulations, has had more on/offs during the days of the cooling period, which explains why the energy signatures appear more dispersed during this season. Moreover, the set points selected by the occupants during the cooling season are lower that the set point and setback that were assumed in the simulations for both *R1* (Fig. 13) and *R2* (Fig. 14). During the heating season the set points match the simulation assumptions for *R1*, while in *R2* the occupants have selected a higher set point for most of the period. The occupants' preferences for operating the HVAC in comparison to the simulation assumptions, explain why the discrepancy between the simulation and measured data is greater in cooling season in comparison with the heating season.

As previously presented in Table 3, after calibrating the models according to actual occupancy patterns, the performance gap between the actual performance and simulation results was lessened, achieving a margin of error between simulated and actual performance within acceptable limits.

Table 4
Difference between expected and actual HVAC consumption.

	Residence 1		Residence 2	
	kWh/m^2	%	kWh/m^2	%
June 2019	0.41	+27	0.53	+40
July 2019	0.30	+12	0.39	+19
August 2019	0.22	+10	0.45	+24
September 2019	1.25	+479	1.11	+393
October 2019	0.54	+90	0.60	+104
November 2019	-0.85	-28	1.87	+79
December 2019	-1.90	-33	1.84	+43
January 2020	-1.74	-28	2.05	+45
February 2020	-1.90	-41	1.46	+42
March 2020	-0.23	-9	2.41	+120
April 2020	1.36	+154	1.57	+195
May 2020	1.97	+565	1.06	+312
Total	-0.59	-2	15.36	+64

3.2. Actual performance compared to design targets

The assessment of the performance in relation to the design performance targets is presented in Table 5 where it is confirmed that despite the performance gap caused by unpredictable occupant behavior, the actual performance has satisfied the design targets. The design targets focus on net regulated energy consumption, i.e. (Regulated Energy Consumption) – (RES production). In addition, the performance of the residences and the neighborhood is assessed in the next section with the total consumption taken into account.

3.2.1. Investment cost and overall impact

The target for investment cost reduction was ≥ 16% compared to costs for a single ZEB of similar performance. A 24% investment cost reduction has been achieved.

The investment cost reduction has been calculated as the difference between the investment cost for a zero energy building designed and constructed with the integrated design and construction neighborhood approach (presented in section 0) and a zero energy reference building with equivalent energy performance targets. The investment cost refers to the technologies (energy saving, energy production, energy management, energy storage) that have been used to achieve the energy performance targets.

The overall energy saving, energy cost savings and CO_2 reduction of the pilot ZEN compared to a neighborhood designed and constructed according to the national standard are given in Table 6.

3.3. Zero energy balance

The analysis of PV production data reveals that the neighborhood has been able to achieve the design target for renewable production at the neighborhood level, reaching the value of 50.03 kWh/m^2/year.

3.3.1. Monthly zero energy balance

The monthly production exceeds the total monthly consumption between June 2019 – August 2019 and again from April 2020 onward. The monthly production has exceeded the monthly regulated consumption each month up to October 2019, while from November to January, as expected, it is much lower (Fig. 15 and Table 7). In December and January, 87% of the production is directly consumed by the residences. However, this is enough to cover a small portion of the total demand; accounting also for the battery, 11% of the total consumption is covered by self-consumption and 89% is covered by energy imported from the grid in December. When accounting for the battery, more than half of the total consumption in the pilot is covered by self-consumption for half of the year (63% in May 2020).

Table 7 further illustrates how the balance varies within the year from month to month, as well as the contribution of the storage in consuming self-produced electricity and consequently reducing energy coming from the grid.

3.3.2. One year zero energy balance

Overall, the neighborhood has achieved a positive energy balance on a yearly basis with regards to its regulated energy needs. In fact, the percentage coverage of renewable energy production with respect to the total energy consumption is equal to 66%, while the percentage coverage of renewable energy production with respect to the regulated energy consumption is equal to 128%. (Table 7). In Fig. 16, the cumulative production and cumulative total consumption of the houses and the neighborhood, according to the measured data for the period of June 2019 – May 2020, are displayed. The neighborhood appears to behave as a positive energy neighborhood until October, whereas from November onwards it is a near-zero energy neighborhood.

4. Discussion

The annual performance results that have been obtained from the pilot ZEN in Italy reveal that the design targets for at least 50 kWh/m^2/year RES production at neighborhood level and a maximum of 20 kWh/m^2/year of net regulated energy consumption at building level have been achieved. The energy conservation of the pilot ZEN for the monitored year has been calculated to 75.7% compared to a standard neighborhood. These results are obtained through an integrated approach to design and construction. The performance has been simulated and optimized at neighborhood level, accounting also for microclimate conditions, while costs have been optimized with the specific performance targets as constraints. Through the neighborhood approach that offers the opportunity for customization, the investment cost has been calculated to be 24% lower that the investment cost for a single ZEB of similar performance. The actual performance results and the consequent final simulations calibrated according to monitored use are within an acceptable margin of error 6.36% CV(RMSE) for R1 and 8.15% CV(RMSE) for R2 (with acceptable value < 15% [72]). These results confirm that the design and simulation approach, along with the specific simulation tools are reliable and support the repeatability of the approach towards the transition from single ZEBs to zero energy neighborhoods.

Besides, planning for zero energy at the neighborhood scale is a complex task that involves multiple actors and requires an integrated approach while also setting specific long-term goals for the design [12,66]. This was the approach followed for the specific case study by setting solid performance targets and reaching them through an integrated approach to design, construction and monitoring. The involvement of multiple actors and their alignment towards a common goal has been highlighted in the literature as a challenge of the energy master planning [12]. In fact, it has been one of the challenges and a learning curve during the implementation of the case study that is discussed herein, as analyzed in [90].

The occupants in particular are critical stakeholders. On one hand, occupant behavior and interaction with the building and its systems are a major source of the performance gap [30,50]. This has been confirmed by the monitored performance results presented in this paper and the observed deviation from initial simulations where standard user-profiles and behavior had been assumed. The occupants in both buildings had the tendency to operate the HVAC in a tighter temperature range than the set-point/setback range assumed in simulations. In addition, they selected continuous system operation. Although the continuous operation has led to smaller indoor temperature fluctuations, intermittent operation with a setback temperature (as assumed in the simulations) could lead to lower consumption. One step further, occupant/citizen engagement and awareness are critical for their acceptance of shared technologies and energy community schemes and consequently for the planning and uptake of zero energy neighborhoods [7,90,91] especially

Table 5
Performance of the residences and neighborhood during one year according to the design targets, June 2019 – May 2020.

		Residence 1		Residence 2	
kWh/m²/y	Design targets	Expected ("as-built")	Real	Expected ("as-built")	Real
Regulated energy use	<70	47.4	**37.61**	47.5	**41.44**
Renewable energy (neighbourhood level)	>50	49.7	**50.03**	49.7	**50.03**
Net regulated energy	<20	-2.3	**-12.7**	-2.2	**-8.6**

Table 6
Energy conservation, CO_2 emissions reduction and energy cost savings for the first year of the pilot ZEN monitoring.

	Electricity Consumption (kWh)[1]	Electricity Conservation (kWh)	CO_2 emissions reduction (tonnes)[2]	Cost Savings (euro)[3]
Pilot ZEN	6502	20243	6.84	4655.89
Standard neighborhood	26745			

[1] For the pilot ZEN the net electricity consumption for one year has been calculated. The standard neighborhood is assumed to not have RES and present the same energy conservations of the pilot ZEN.
[2] The CO_2 emissions conversion was assumed 0.338 tn/MWh according to [88].
[3] The household electricity price for Italy is 0.23€/kWh according to [89].

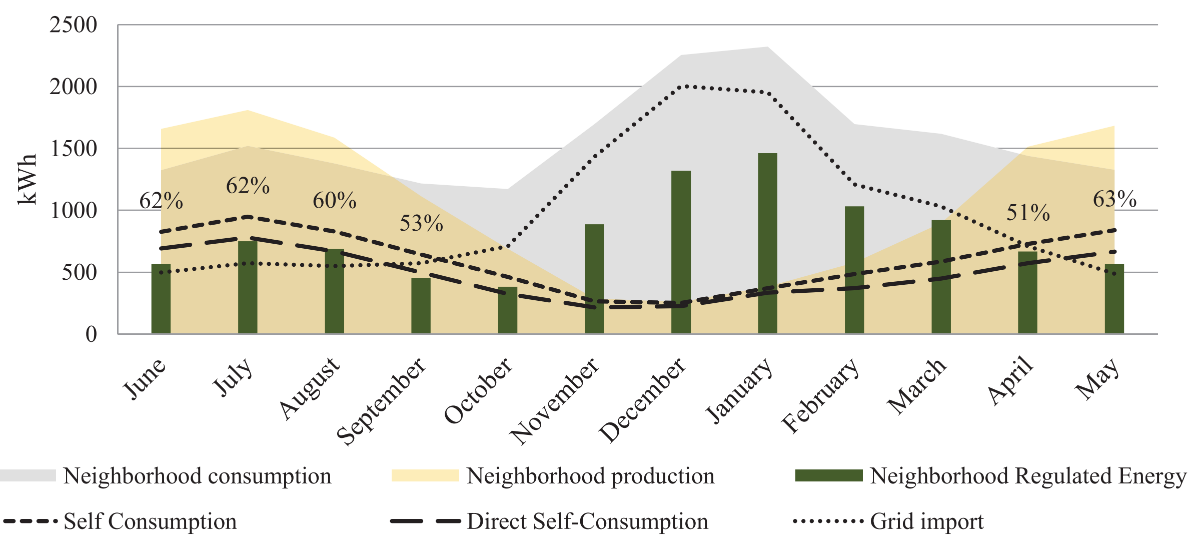

Fig. 15. Monthly PV production against total consumption for the neighborhood. Direct self-consumption represents energy produced by the PV that is consumed directly by the neighborhood. Self-consumption includes the energy from the batteries.

Table 7
Zero energy balance and self-consumption percentage per month and the whole year. Legend: orange >100, ochre between 50 and 100, grey < 50

	PV Prod. / Tot. Cons.	PV Prod. / Reg. Cons.	Direct Self-Cons./ PV Prod.	Self-Cons / PV Prod.	Self-Cons / Tot. Cons.	Self-Cons / Reg. Cons.
J	125%	293%	42%	50%	62%	146%
J	119%	241%	43%	52%	62%	126%
A	115%	231%	42%	52%	60%	120%
S	92%	245%	45%	58%	53%	142%
O	59%	180%	47%	67%	39%	120%
N	17%	32%	74%	92%	16%	30%
D	12%	20%	87%	97%	11%	19%
J	17%	26%	87%	96%	16%	25%
F	34%	56%	64%	84%	29%	47%
M	55%	97%	50%	65%	36%	64%
A	105%	226%	38%	48%	51%	109%
M	127%	298%	40%	50%	63%	149%
Year	66%	**128%**	47%	58%	38%	75%

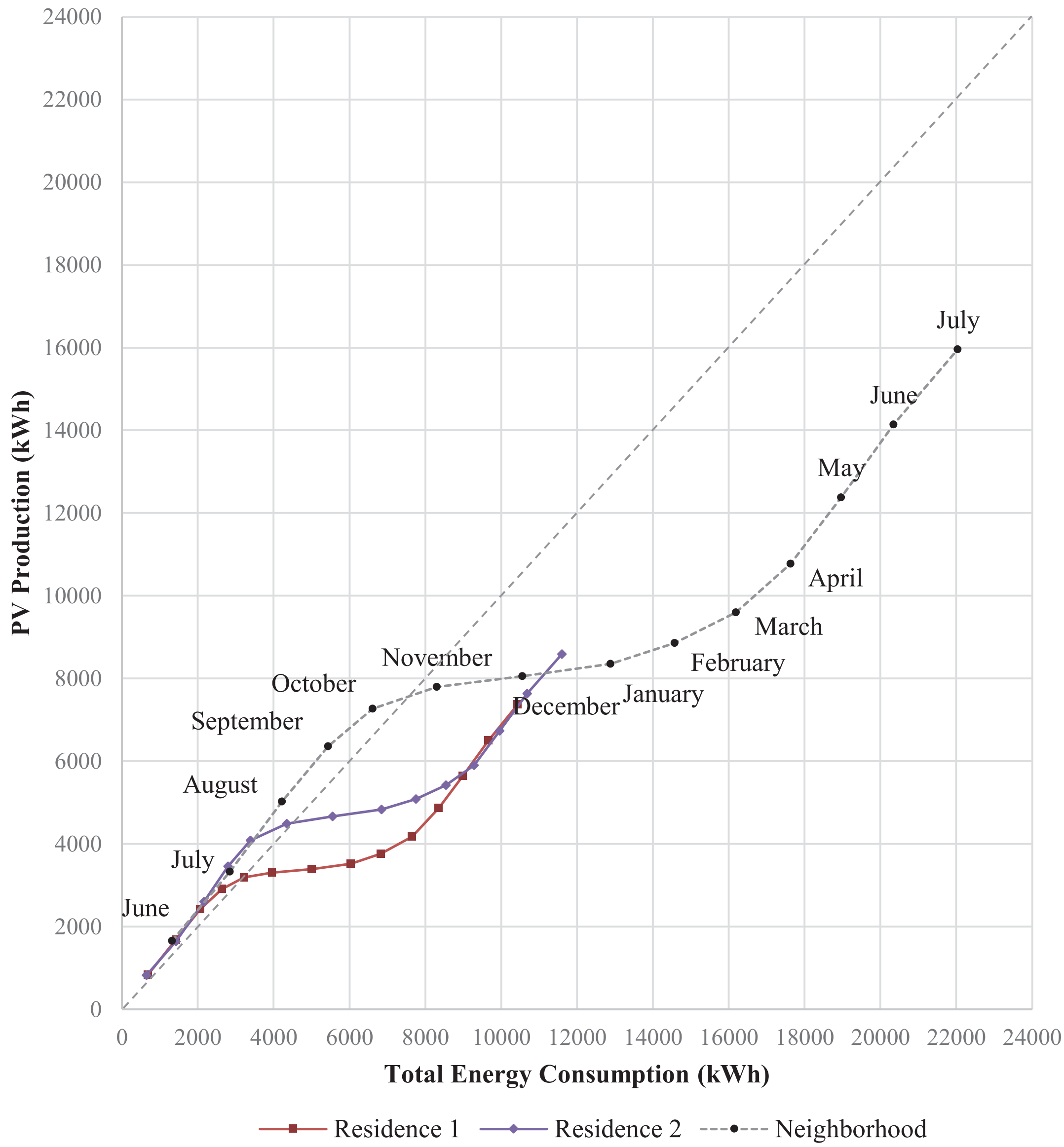

Fig. 16. Cumulative energy consumption of the houses and the neighborhood vs cumulative PV production during the period June 2019 – July 2020.

in view of the raise of the future smart and clean energy communities [92,93].

When considering the total consumption and total PV production of the neighborhood for the first year, it has behaved as a positive energy neighborhood for the first five months of monitoring, whereas for the remaining months it behaved as a near-zero energy neighborhood. Overall the PV production during one year in the pilot neighborhood can compensate for its regulated energy consumption. In this sense, the neighborhood can be characterized as “net zero regulated energy” and is compatible with the definition of the EPBD when transposing the near zero energy building description to the neighbourhood scale. In fact, the neighborhood was designed with a focus on regulated energy performance targets. Nonetheless, existing definitions consider the total (regulated + unregulated) energy needs of the buildings in the balance calculation. Therefore, higher RES production would be needed to balance the total building energy needs of the neighborhood in order to be a net zero energy neighborhood.

PV production, in particular, can only partly be consumed directly in the neighborhood as a result of the temporal mismatch between production and consumption that can be traced from the yearly and monthly level down to the daily level [20,40]. In the case study, although yearly PV production balances the regulated energy consumption, looking at the monthly breakdown, PV production exceeds the regulated energy needs for only seven months. Moreover, direct self-consumption ranges from 38% to 87%. The latter though is observed in December and January when production is already low (20% and 26% of the regulated energy consumption respectively). When accounting also for the batteries, self-consumption has been increased on average by 25% within the monitored year.

PV coverage reported in the state of the art has been higher than the coverage achieved in the pilot ZEN. Implementation of demand-side management (DSM) schemes to manage loads (e.g. shift peak loads) and schedule storage charge/discharge can improve the mismatch for approaching a true zero energy balance where non-renewable needs can be minimized [20,48]. When equipped with smart DSM operations, the ZENs are prepared to get integrated into the new decentralized smart grids where energy flows and energy costs can be optimally managed [20,94]. Finally, using one common battery for the neighborhood, i.e. community storage, instead of separate batteries could be a more efficient option from energy and economic perspectives [95].

Monitoring installations for performance monitoring, evaluation, and energy management then become an indispensable component for the zero energy neighborhood. In the case study, analysis of the performance is facilitated by real monitored data that are collected through a comprehensive monitoring schema on a specifically developed Web-GIS monitoring platform. The platform can support performance analysis and performance targets monitoring as well as smart capabilities for energy management. Critical to reliable performance evaluation and future integration of energy management and smart operations is the collection of high-quality data. To this end, data quality control, evaluation, and improvement procedures have been adopted as part of the project's monitoring, measurement, and verification. In the case study, the quality control procedures that have been implemented during design and installation have contributed to the collection of high-quality datasets. However, the monitoring campaign has experienced extenuating circumstances. The lockdown due to COVID19 has prevented technical support to reach the neighborhood for problem-solving of monitoring equipment dysfunction between February 2020 and July 2020. Although this might be considered an exception, it is an aspect that needs to be reviewed and problem-solving adjustments to be made accordingly to ensure quality data collection. Therefore, continuous recording of problems and of causes of problems needs to be part of the monitoring campaign to allow for maintaining and improving data quality and consequently reliability of performance monitoring, evaluation, and energy management of the neighborhood.

5. Conclusions

The zero energy concept is at the forefront of the high performing built environment, with attention being transferred from single buildings to building complexes. This transfer of interest is relevant to the role that cities are expected to have in the fight against climate change and in particular in the decarbonisation of the energy landscape. The present paper provides specific net regulated performance targets for residential buildings within ZEN, it also provides specific renewable production targets for ZEN and proves that both targets are achievable with reduced costs following an integrated design, construction, and monitoring methodology. Continuous monitoring for measuring and verifying the expected performance is an indispensable activity and a holistic and comprehensive monitoring methodology has been adopted for the case study.

Limitations and further research opportunities can be summarized as follows:

- The current pilot is composed of 2 buildings and is a new development. However, the approach is transferable to bigger neighborhoods as well as to existing neighborhoods. Implementation and consequent results from diverse developments will help study the transferability of this approach in practice.
- The discussed results have been obtained from the first year of monitoring. Further monitoring results will help evaluate the performance of the ZEN in the long-term.
- The first year of monitoring includes three months in lockdown, from March to May 2020. The effect on the lockdown in the measured consumption remains to be further studied.
- Currently, a "positive regulated energy" neighborhood has been achieved. Higher RES production and implementation of DSM could improve the zero energy balance for the total energy needs and minimization of non-renewable energy consumption.
- Currently, no real sharing of production or storage is implemented in the neighborhood, owing to lack of relevant regulations the time of its construction. This project supported the development and introduction of new regulations in Italy for community energy sharing, ready for implementation from November 2020. Community energy sharing and community storage has shown potential to provide improved balance results for the future zero energy and smart communities. This project can become one of the very first sharing full scale examples in Italy, to explore sharing scheme implementation.

Through all stages, from design to monitoring, this pilot neighborhood was an opportunity to learn by the implementation of a bespoke approach and real data, there lies its significance. More results from realized projects are needed for further boosting the zero energy concept uptake at neighborhood scale and paving the way to future clean energy neighborhoods.

Acknowledgements

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References

[1] IPEEC building energy efficiency taskgroup zero energy building definitions and policy activity an international review, n.d. 2021

[2] M. Santamouris, Innovating to zero the building sector in Europe: minimising the energy consumption, eradication of the energy poverty and mitigating the local climate change, Sol. Energy. 128 (2016) 61–94, doi:10.1016/j.solener.2016.01.021.

[3] C. Becchio, S.P. Corgnati, C. Delmastro, V. Fabi, P. Lombardi, The role of nearly-zero energy buildings in the definition of postcarbon cities, in: Energy Procedia, Elsevier Ltd, 2015, pp. 687–692, doi:10.1016/j.egypro.2015.11.067.

[4] F.M. Butera, Zero-energy buildings: the challenges, Adv. Build. Energy Res. 7 (2013) 51–65, doi:10.1080/17512549.2012.756430.

[5] P. Torcellini, D.B. Crawley, Understanding zero-energy buildings, ASHRAE J (2006).

[6] A.F. Marique, S. Reiter, A simplified framework to assess the feasibility of zero-energy at the neighbourhood/community scale, Energy Build 82 (2014) 114–122, doi:10.1016/j.enbuild.2014.07.006.

[7] A. Mittal, C.C. Krejci, M.C. Dorneich, D. Fickes, An agent-based approach to modeling zero energy communities, Sol. Energy. 191 (2019) 193–204, doi:10.1016/j.solener.2019.08.040.

[8] R. Hledik, B. Tsuchida, J. Palfreyman, Beyond Zero Net Energy? Alternative Approaches to Enhance Consumer and Environmental Outcomes, 2018.

[9] A.J. Marszal, P. Heiselberg, J.S. Bourrelle, E. Musall, K. Voss, I. Sartori, A. Napolitano, Zero energy building - a review of definitions and calculation methodologies, Energy Build 43 (2011) 971–979, doi:10.1016/j.enbuild.2010.12.022.

[10] K. Voss, I. Sartori, R. Lollini, Nearly-zero, net zero and plus energy buildings – How definitions & regulations affect the solutions, The REHVA (2012).

[11] I. Sartori, A. Napolitano, K. Voss, Net zero energy buildings: a consistent definition framework, Energy Build 48 (2012) 220–232, doi:10.1016/j.enbuild.2012.01.032.

[12] S. Charani Shandiz, B. Rismanchi, G. Foliente, Energy master planning for net-zero emission communities: State of the art and research challenges, Renew. Sustain. Energy Rev. 137 (2021), doi:10.1016/j.rser.2020.110600.

[13] K.R. Ullah, V. Prodanovic, G. Pignatta, A. Deletic, M. Santamouris, Technological advancements towards the net-zero energy communities: a review on 23 case studies around the globe, Sol. Energy. 224 (2021) 1107–1126, doi:10.1016/J.SOLENER.2021.06.056.

[14] A. Sharifi, Y. Yamagata, Principles and criteria for assessing urban energy resilience: A literature review, Renew. Sustain. Energy Rev. 60 (2016) 1654–1677, doi:10.1016/j.rser.2016.03.028.

[15] I. Vandecasteele, C. Baranzelli, A. Siragusa, J.P. (Eds. . Aurambout, V. Alberti, M. Alonso Raposo, C. Attardo, D. Auteri, R. Barranco, F. Batista e Silva, P. Benczur, P. Bertoldi, F. Bono, I. Bussolari, S. Caldeira, J. Carlsson, P. Christidis, A. Christodoulou, B. Ciuffo, S. Corrado, C. Fioretti, M.C. Galassi, L. Galbusera, B. Gawlik, F. Giusti, J. Gomez, M. Grosso, Â. Guimarães Pereira, C. Jacobs-Crisioni, B. Kavalov, M. Kompil, A. Kucas, A. Kona, C. Lavalle, A. Leip, L. Lyons, A.R. Manca, M. Melchiorri, F. Monforti-Ferrario, V. Montalto, B. Mortara, F. Natale, F. Panella, G. Pasi, C. Perpiña, M. Pertoldi, E. Pisoni, A. Polvora, A. Rainoldi, D. Rembges, G. Rissola, S. Sala, S. Schade, N. Serra, L. Spirito, A. Tsakalidis, M. Schiavina, G. Tintori, L. Vaccari, T. Vandyck, D. Vanham, S. Van Heerden, C. Van Noordt, M. Vespe, N. Vetters, N. Vilahur Chiaraviglio, P. Vizcaino, U. Von Estorff, G. Zulian, The Future of Cities – Opportunities, challenges and the way forward, Luxembourg, 2019. doi:10.2760/375209.

[16] M. Villa-Arrieta, A. Sumper, Economic evaluation of nearly zero energy cities, Appl. Energy 237 (2019) 404–416, doi:10.1016/j.apenergy.2018.12.082.

[17] J. Zapata Riveros, M. Kubli, S. Ulli-Beer, Prosumer communities as strategic allies for electric utilities: Exploring future decentralization trends in Switzerland, Energy Res. Soc. Sci. 57 (2019), doi:10.1016/j.erss.2019.101219.

[18] S. Koutra, C. Pagnoule, N.-F. Galatoulas, A. Bagheri, T. Waroux, V. Becue, C.S. Ioakimidis, The zero-energy idea in districts: application of a methodological approach to a case study of Epinlieu (Mons), Sustain 11 (4814) (2019) 11 (2019) 4814, doi:10.3390/SU11174814.

[19] A.R. Amaral, E. Rodrigues, A. Rodrigues Gaspar, Á. Gomes, Review on performance aspects of nearly zero-energy districts, Sustain. Cities Soc. 43 (2018) 406–420, doi:10.1016/j.scs.2018.08.039.

[20] A. Koch, S. Girard, K. McKoen, Towards a neighbourhood scale for low- or zero-carbon building projects, Build. Res. Inf. 40 (2012) 527–537, doi:10.1080/09613218.2012.683241.

[21] N. Carlisle, A. Otto, V. Geet, S. Pless, Definition of a "Zero Net Energy" Community, 2009. http://www.osti.gov/bridge (accessed March 25, 2020).

[22] US Department of Energy, A COMMON DEFINITION FOR ZERO ENERGY BUILDINGS. Prepared for the U.S. Department of Energy by The National Institute of Building Sciences, 2015.
[23] EU, Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast), Off. J. Eur. Union. (2010) 13–35, doi:10.3000/17252555.L_2010.153.eng.
[24] S. Koutra, V. Becue, M.A. Gallas, C.S. Ioakimidis, Towards the development of a net-zero energy district evaluation approach: a review of sustainable approaches and assessment tools, Sustain. Cities Soc. 39 (2018) 784–800, doi:10.1016/j.scs.2018.03.011.
[25] C. Piselli, M. Di Grazia, A.L. Pisello, Combined effect of outdoor microclimate boundary conditions on air conditioning system's efficiency and building energy demand in net zero energy settlements, Sustainability 12 (2020) 6056, doi:10.3390/su12156056.
[26] T. Yang, X. Zhang, Benchmarking the building energy consumption and solar energy trade-offs of residential neighborhoods on Chongming Eco-Island, China, Appl. Energy 180 (2016) 792–799, doi:10.1016/j.apenergy.2016.08.039.
[27] M. Cardinali, A.L. Pisello, C. Piselli, I. Pigliautile, F. Cotana, Microclimate mitigation for enhancing energy and environmental performance of near zero energy settlements in Italy, Sustain. Cities Soc. 53 (2020) 101964, doi:10.1016/j.scs.2019.101964.
[28] V. Sougkakis, K. Lymperopoulos, N. Nikolopoulos, N. Margaritis, P. Giourka, K. Angelakoglou, An Investigation on the feasibility of near-zero and positive energy communities in the Greek context, Smart Cities 3 (2020) 362–384, doi:10.3390/smartcities3020019.
[29] M.K. Nematchoua, A. Marie-Reine Nishimwe, S. Reiter, Towards nearly zero-energy residential neighbourhoods in the European union: a case study, Renew. Sustain. Energy Rev. 135 (2021) 110198, doi:10.1016/j.rser.2020.110198.
[30] A. Roser, K. Schakib-Ekbatan, V. Weiler, U. Eicker, R. Lohse, Net zero energy strategies and planning support tools for campuses and residential neighborhoods in Germany, ASHRAE Trans 126 (2020) 849–856.
[31] M.M. Rafique, S. Rehman, L.M. Alhems, Developing zero energy and sustainable villages – A case study for communities of the future, Renew. Energy. 127 (2018) 565–574, doi:10.1016/j.renene.2018.04.087.
[32] P. Sokolnikova, P. Lombardi, B. Arendarski, K. Suslov, A.M. Pantaleo, M. Kranhold, P. Komarnicki, Net-zero multi-energy systems for Siberian rural communities: a methodology to size thermal and electric storage units, Renew. Energy. 155 (2020) 979–989, doi:10.1016/j.renene.2020.03.011.
[33] Y. Lu, Z. Khan, H. Gunduz, W. Wang, J. Li, X.P. Zhang, Economic performance of net-zero energy community under reward-penalty mechanism considering PV system reliability, Environ. Clim. Technol. 23 (2019) 26–42, doi:10.2478/rtuect-2019-0077.
[34] C. Becchio, M.C. Bottero, S.P. Corgnati, F. Dell'Anna, Decision making for sustainable urban energy planning: an integrated evaluation framework of alternative solutions for a NZED (Net Zero-Energy District) in Turin, Land Use Policy 78 (2018) 803–817, doi:10.1016/j.landusepol.2018.06.048.
[35] C. Hachem-Vermette, F. Guarino, V.La Rocca, M. Cellura, Towards achieving net-zero energy communities: investigation of design strategies and seasonal solar collection and storage net-zero, Sol. Energy. 192 (2019) 169–185, doi:10.1016/j.solener.2018.07.024.
[36] M.H. Kim, D. Kim, J. Heo, D.W. Lee, Techno-economic analysis of hybrid renewable energy system with solar district heating for net zero energy community, Energy (2019) 187, doi:10.1016/j.energy.2019.115916.
[37] F. Ascione, N. Bianco, R.F. De Masi, M. Dousi, S. Hionidis, S. Kaliakos, E. Mastrapostoli, M. Nomikos, M. Santamouris, A. Synnefa, G.P. Vanoli, K. Vassilakopoulou, Design and performance analysis of a zero-energy settlement in Greece, Int. J. Low-Carbon Technol. 12 (2017) 141–161, doi:10.1093/ijlct/ctw003.
[38] A. Janzadeh, M. Zandieh, Design feasibility of a net-zero energy neighborhood in Qazvin, Energy Effic 14 (2021) 1–21, doi:10.1007/s12053-020-09909-w.
[39] R.M. Gonzalez, B. Asare-Bediako, J.F.G. Cobben, W.L. Kling, G. Scharrenberg, D. Dijkstra, Distributed energy resources for a zero-energy neighborhood, IEEE PES Innov. Smart Grid Technol. Conf. Eur, 2012, doi:10.1109/ISGTEurope.2012.6465820.
[40] R.W. Hammon, Applications for large residential communities: what is net-zero energy? Strateg. Plan. Energy Environ. 29 (2010) 26–55, doi:10.1080/10485231009595086.
[41] T. Fujimoto, Y. Yamaguchi, Y. Shimoda, Energy management for voltage control in a net-zero energy house community considering appliance operation constraints and variety of households, Energy Build 147 (2017) 188–199, doi:10.1016/j.enbuild.2017.05.009.
[42] M.H. Kim, D. Kim, J. Heo, D.W. Lee, Energy performance investigation of net plus energy town: Energy balance of the Jincheon eco-friendly energy town, Renew. Energy. 147 (2020) 1784–1800, doi:10.1016/j.renene.2019.09.113.
[43] K. Gaiser, P. Stroeve, The impact of scheduling appliances and rate structure on bill savings for net-zero energy communities: application to West Village, Appl. Energy. 113 (2014) 1586–1595, doi:10.1016/j.apenergy.2013.08.075.
[44] E. Kalaycıoğlu, A.Z. Yılmaz, A new approach for the application of nearly zero energy concept at district level to reach EPBD recast requirements through a case study in Turkey, Energy Build 152 (2017) 680–700, doi:10.1016/j.enbuild.2017.07.040.
[45] J. Burch, J. Woods, E. Kozubal, A. Boranian, Zero energy communities with central solar plants using liquid desiccants and local storage, in: Energy Procedia, Elsevier Ltd, 2012, pp. 55–64, doi:10.1016/j.egypro.2012.11.008.
[46] H.S. Nam, S.J. Lee, T.H. Kim, Y.K. Hong, Y.K. Jeong, Optimization mechanism of energy cluster for zero energy town, in: Int. Conf. Inf. Commun. Technol. Converg. ICT Converg. Technol. Lead. Fourth Ind. Revolution, ICTC 2017, Institute of Electrical and Electronics Engineers Inc., 2017, pp. 1121–1123, doi:10.1109/ICTC.2017.8190873.
[47] R.A. Lopes, J. Martins, D. Aelenei, C.P. Lima, A cooperative net zero energy community to improve load matching, Renew. Energy. 93 (2016) 1–13, doi:10.1016/j.renene.2016.02.044.
[48] R. De Coninck, R. Baetens, D. Saelens, A. Woyte, L. Helsen, Rule-based demand-side management of domestic hot water production with heat pumps in zero energy neighbourhoods, J. Build. Perform. Simul. 7 (2014) 271–288, doi:10.1080/19401493.2013.801518.
[49] H. Karunathilake, K. Hewage, W. Mérida, R. Sadiq, Renewable energy selection for net-zero energy communities: Life cycle based decision making under uncertainty, Renew. Energy. 130 (2019) 558–573, doi:10.1016/j.renene.2018.06.086.
[50] C. Hammer, West Village Case Study: Designers and Occupants, n.d. http://www.pge.com/mybusiness/energysavingsrebates/rebatesincentives/znepilotprogram/ (accessed February 2, 2021).
[51] European Commission, The European green deal, Eur. Comm. (2019), doi:10.1017/CBO9781107415324.004.
[52] C. Zhang, C. Cui, Y. Zhang, J. Yuan, Y. Luo, W. Gang, A review of renewable energy assessment methods in green building and green neighborhood rating systems, Energy Build 195 (2019) 68–81, doi:10.1016/j.enbuild.2019.04.040.
[53] O. Lindholm, H.U. Rehman, F. Reda, Positioning positive energy districts in European cities, Buildings (2021), doi:10.3390/buildings11010019.
[54] S. Soutullo, L. Aelenei, P.S. Nielsen, J.A. Ferrer, H. Gonçalves, Testing platforms as drivers for positive-energy living laboratories, Energies (2020), doi:10.3390/en13215621.
[55] A. Napolitano, F. Noris, R. Lollini, Measurement and Verification protocol for Net Zero Energy Buildings, IEA SHC/ECBS Task 40/Annex 52. (2013).
[56] D. Crawley, S. Pless, P. Torcellini, Getting to Net Zero, 2009. http://www.osti.gov/bridge (accessed March 18, 2020).
[57] G. Artopoulos, G. Pignatta, M. Santamouris, From the sum of near-zero energy buildings to the whole of a near-zero energy housing settlement: the role of communal spaces in performance-driven design, Architecture_MPS (2018), doi:10.14324/111.444.amps.2018v14i3.001.
[58] M. Ferrara, V. Monetti, E. Fabrizio, Cost-optimal analysis for nearly zero energy buildings design and optimization: a critical review, Energies 11 (2018) 1478, doi:10.3390/en11061478.
[59] C. Piselli, A.L. Pisello, Occupant behavior long-term continuous monitoring integrated to prediction models: Impact on office building energy performance, Energy 176 (2019) 667–681, doi:10.1016/j.energy.2019.04.005.
[60] N. Kampelis, K. Gobakis, V. Vagias, D. Kolokotsa, L. Standardi, D. Isidori, C. Cristalli, F.M. Montagnino, F. Paredes, P. Muratore, L. Venezia, K. Dracou, A. Montenon, A. Pyrgou, T. Karlessi, M. Santamouris, Evaluation of the performance gap in industrial, residential & tertiary near-Zero energy buildings, Energy Build 148 (2017) 58–73, doi:10.1016/j.enbuild.2017.03.057.
[61] C. Carpino, E. Loukou, P. Heiselberg, N. Arcuri, Energy performance gap of a nearly Zero Energy Building (nZEB) in Denmark: the influence of occupancy modelling, Build. Res. Inf. (2020) 1–23, doi:10.1080/09613218.2019.1707639.
[62] D. Kolokotsa, D. Rovas, E. Kosmatopoulos, K. Kalaitzakis, A roadmap towards intelligent net zero- and positive-energy buildings, Sol. Energy. 85 (2011) 3067–3084, doi:10.1016/j.solener.2010.09.001.
[63] V.L. Castaldo, A.L. Pisello, C. Piselli, C. Fabiani, F. Cotana, M. Santamouris, How outdoor microclimate mitigation affects building thermal-energy performance: a new design-stage method for energy saving in residential near-zero energy settlements in Italy, Renew. Energy. 127 (2018) 920–935, doi:10.1016/j.renene.2018.04.090.
[64] S. Isaac, S. Shubin, G. Rabinowitz, Cost-optimal net zero energy communities, Sustainability. 12 (2020) 2432, doi:10.3390/su12062432.
[65] M.S. Todorović, BPS, energy efficiency and renewable energy sources for buildings greening and zero energy cities planning: harmony and ethics of sustainability, Energy Build 48 (2012) 180–189, doi:10.1016/j.enbuild.2012.01.027.
[66] A.M. Zhivov, M. Case, R. Liesen, J. Kimman, W. Broers, Energy Master Planning Towards Net-Zero Energy Communities/Campuses, (2013). https://apps.dtic.mil/sti/citations/AD1049051 (accessed January 23, 2021).
[67] A. Synnefa, M. Laskari, R. Gupta, A.L. Pisello, M. Santamouris, Development of net zero energy settlements using advanced energy technologies, in: Procedia Eng., Elsevier Ltd, 2017, pp. 1388–1401, doi:10.1016/j.proeng.2017.04.302.
[68] ZERO-PLUS, Designing Net Zero Energy (NZE) Settlements - Tools and Methods, 2020.
[69] D.B. Crawley, C.O. Pedersen, L.K. Lawrie, F.C. Winkelmann, EnergyPlus: Energy Simulation Program, ASHRAE J. 42 (2000) 49–56. http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.122.6852 (accessed July 12, 2020).
[70] Meteotest, Meteonorm Software, (2016). https://meteonorm.com (accessed May 21, 2020).
[71] I.A. Meir, S. Isaac, D. Kolokotsa, K. Gobakis, G. Pignatta, Towards zero energy settlements - a brief note on commissioning and POE within the EU ZeroPlus settlements, IOP Conf. Ser. Earth Environ. Sci., Institute of Physics Publishing, 2020, doi:10.1088/1755-1315/410/1/012038.
[72] ASHRAE, ASHARE Guidelines 14 - Measurement of energy and demand savings., 8400 (2002) 1–165.
[73] A. Mavrigiannaki, K. Gobakis, D. Kolokotsa, K. Kalaitzakis, A.L. Pisello, C. Piselli, R. Gupta, M. Gregg, M. Laskari, M. Saliari, M.-N. Assimakopoulos, A. Synnefa, Measurement and verification of zero energy settlements: lessons learned from four pilot cases in Europe, Sustainability 12 (2020) 9783, doi:10.3390/su12229783.
[74] K. Gobakis, A. Mavrigiannaki, K. Kalaitzakis, D.D. Kolokotsa, Design and development of a Web based GIS platform for zero energy settlements monitoring, in: Energy Procedia, Elsevier Ltd, 2017, pp. 48–60, doi:10.1016/j.egypro.2017.09.598.
[75] L. Richardson, S. Ruby, RESTful web services, O'Reilly, 2007.

[76] C. Batini, C. Cappiello, C. Francalanci, A. Maurino, Methodologies for data quality assessment and improvement, ACM Comput. Surv. 41 (2009) 1–52, doi:10.1145/1541880.1541883.
[77] D.G.T. Arts, N.F. De Keizer, G.-J. Scheffer, Defining and improving data quality in medical registries: a literature review, case study, and generic framework, J Am Med Inf. Assoc. 9 (2002) 600–611, doi:10.1197/jamia.M1087.
[78] B.P. Weidema, M.S. Wesnæs, Data quality management for life cycle inventories-an example of using data quality indicators, J. Clean. Prod. 4 (1996) 167–174, doi:10.1016/S0959-6526(96)00043-1.
[79] D.M. Strong, Y.W. Lee, R.Y. Wang, Data quality in context, Commun. ACM. 40 (1997) 103–110, doi:10.1145/253769.253804.
[80] T. Nagle, T. Redman, D. Sammon, Assessing data quality: a managerial call to action, Bus. Horiz. 63 (2020) 325–337, doi:10.1016/j.bushor.2020.01.006.
[81] L. Belussi, L. Danza, Method for the prediction of malfunctions of buildings through real energy consumption analysis : Holistic and multidisciplinary approach of Energy Signature, 55 (2012) 715–720.
[82] R. Hitchin, I. Knight, Daily energy consumption signatures and control charts for air-conditioned buildings, Energy Build 112 (2016) 101–109, doi:10.1016/j.enbuild.2015.11.059.
[83] G. Nordström, H. Johnsson, S. Lidelöw, Using the Energy Signature Method to Estimate the Effective U-Value of Buildings, (2013) 35–44. doi:10.1007/978-3-642-36645-1.
[84] R. Zmeureanu, Assessment of the Energy Savings due to the Building Retrofit, 25 (1990) 95–103.
[85] A. Acquaviva, D. Apiletti, A. Attanasio, E. Baralis, L. Bottaccioli, F.B. Castagnetti, T. Cerquitelli, S. Chiusano, E. Macii, D. Martellacci, E. Patti, Energy signature analysis: knowledge at your fingertips, in: 2015 IEEE Int. Congr. Big Data, IEEE, 2015, pp. 543–550, doi:10.1109/BigDataCongress.2015.85.
[86] B. Arregi, R. Garay, Regression analysis of the energy consumption of tertiary buildings, Energy Procedia 122 (2017) 9–14, doi:10.1016/j.egypro.2017.07.290.
[87] UK Department for Communities and Local Government (DCLG), UK's national calculation method for non domestic buildings, (2004). http://www.uk-ncm.org.uk/.
[88] carbonfootprint.com - International Electricity Factors, (2020). https://www.carbonfootprint.com/international_electricity_factors.html (accessed February 28, 2021).
[89] Italy: household electricity price 2017-2018 | Statista, (n.d.). https://www.statista.com/statistics/881421/household-electricity-price-in-italy/ (accessed February 28, 2021).
[90] A. Mavrigiannaki, G. Pignatta, M. Assimakopoulos, M. Isaac, R. Gupta, D. Kolokotsa, M. Laskari, M. Saliari, I.A. Meir, S. Isaac, Examining the benefits and barriers for the implementation of net zero energy settlements, Energy Build 230 (2021) 110564, doi:10.1016/j.enbuild.2020.110564.
[91] V. Azarova, J. Cohen, C. Friedl, J. Reichl, Designing local renewable energy communities to increase social acceptance: evidence from a choice experiment in Austria, Germany, Italy, and Switzerland, Energy Policy 132 (2019) 1176–1183, doi:10.1016/j.enpol.2019.06.067.
[92] E.M. Gui, I. MacGill, Typology of future clean energy communities: An exploratory structure, opportunities, and challenges, Energy Res. Soc. Sci. 35 (2018) 94–107, doi:10.1016/j.erss.2017.10.019.
[93] F. Ceglia, P. Esposito, E. Marrasso, M. Sasso, From smart energy community to smart energy municipalities: Literature review, agendas and pathways, J. Clean. Prod. 254 (2020), doi:10.1016/j.jclepro.2020.120118.
[94] O. Van Cutsem, D. Ho Dac, P. Boudou, M. Kayal, Cooperative energy management of a community of smart-buildings: a Blockchain approach, Int. J. Electr. Power Energy Syst. 117 (2020), doi:10.1016/j.ijepes.2019.105643.
[95] E. Barbour, D. Parra, Z. Awwad, M.C. González, Community energy storage: a smart choice for the smart grid? Appl. Energy. 212 (2018) 489–497, doi:10.1016/j.apenergy.2017.12.056.