TECHNICAL UNIVERSITY OF CRETE – SCHOOL OF ENVIRONMENTAL ENGINNERING

Integrated and Smart Design for Buildings and Communities

Ολοκληρωμένος και Ευφυής Σχεδιασμός Κτηρίων και Κοινοτήτων

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ΠΕΡΙΛΗΨΗ

Η ιδέα της μηδενικής ενεργειακής κατανάλωσης βρίσκεται στο επίκεντρο των στόχων για εξοικονόμηση ενέργειας και μείωση εκπομπών διοξειδίου του άνθρακα στο δομημένο περιβάλλον. Η διεύρυνση εφαρμογής της ιδέας πέρα από την κλίμακα του κτηρίου δύναται να ξεπεράσει τους περιορισμούς που έχουν μεμονωμένα κτήρια στην επίτευξη μηδενικής ενεργειακής κατανάλωσης και σχετίζονται με τη χρήση, το μέγεθος, τη διαθεσιμότητα επιτόπιας ανανεώσιμης ενέργειας και το κόστος.

Ο σχεδιασμός κτηρίων υπόκειται μια μεταβολή αντίληψης με την εμφάνιση της έννοιας του Ολοκληρωμένου Σχεδιασμού. Ο Ολοκληρωμένος Σχεδιασμός προϋποθέτει τη συμμετοχή πολλών και ποικίλων ειδικοτήτων από την αρχή του έργου και επίσης ακολουθεί πορεία ανατροφοδότησης ανάμεσα στα στάδια εξέλιξής του.

Για το σχεδιασμό και τη λειτουργία κτηρίων και κοινοτήτων μηδενικής ενεργειακής κατανάλωσης, η μέτρηση και επαλήθευση της ενεργειακής τους συμπεριφοράς αναγνωρίζεται ως κρίσιμη διαδικασία. Ως αποτέλεσμα, πληθώρα δεδομένων γίνονται διαθέσιμα μέσω μετρητών και αισθητήρων που διαμορφώνουν ένα διασυνδεδεμένο δίκτυο γνώσης. Ο συνδυασμός της γνώσης που προσφέρουν τα δεδομένα με τη δύναμη της τεχνητής νοημοσύνης, οδηγεί στη δημιουργία του έξυπνου δομημένου περιβάλλοντος.

Στην τρέχουσα βιβλιογραφία, οι κοινότητες μηδενικής ενεργειακής κατανάλωσης προσεγγίζονται κυρίως θεωρητικά και απουσιάζει η εμπειρία εφαρμοσμένων περιπτώσεων. Η παρούσα εργασία συμβάλλει παρουσιάζοντας την ολοκληρωμένη προσέγγιση που έχει εφαρμοστεί σε τέσσερις πιλοτικές γειτονιές μηδενικής ενεργειακής κατανάλωσης, καθώς και τα διδάγματα της εφαρμογής. Η εμπειρία που αποκτήθηκε από την ολοκληρωμένη προσέγγιση στο σχεδιασμό, κατασκευή και μέτρηση των πιλοτικών γειτονιών ανέδειξε δύο κύρια ζητήματα: 1) Εξωτερικά εμπόδια που προκύπτουν από τον αστικό σχεδιασμό και τη νομοθεσία και 2) τις προκλήσεις διαχείρισης και ενσωμάτωσης των προσδοκιών και των απαιτήσεων των μελών της ομάδας.

Για να ξεπεραστούν αυτά τα εμπόδια διασφαλίζοντας παράλληλα τα οφέλη της προσέγγισης, η διαχείριση τέτοιων έργων πρέπει να επικεντρωθεί εξαρχής στην καθιέρωση μιας δομής διαχείρισης έργου που θα διασφαλίζει το συντονισμό και την ενσωμάτωση όλων των ενδιαφερόμενων μελών. Η χρήση ενός τυποποιημένου

πρωτοκόλλου συνεργασίας που υιοθετείται από το προκαταρκτικό στάδιο σχεδιασμού, μπορεί να διευκολύνει μελλοντικά έργα. Επιπλέον, χρειάζεται η επικαιροποίηση της νομοθεσίας και των κανονισμών προς τη διευκόλυνση της υλοποίησης έργων που αφορούν κοινότητες μηδενικής ενεργειακής κατανάλωσης.

Προς το παρόν, είναι περιορισμένη η εφαρμογή ενδελεχών διαδικασιών μέτρησης και επαλήθευσης κατά το σχεδιασμό, την παράδοση και τη λειτουργία κατοικιών και κοινοτήτων μηδενικής ενέργειας. Εστιάζοντας στο πλαίσιο μέτρησης και επαλήθευσης που έχει σχεδιαστεί και εφαρμοστεί στις τέσσερις πιλοτικές γειτονιές, έχει ενσωματώσει οδηγίες από τα υπάρχοντα πρωτόκολλα, συνδέεται με τις φάσεις ανάπτυξης του έργου και συμπληρώνεται με τα διδάγματα που αντλήθηκαν μέσω της εφαρμογής. Το τελικό πλαίσιο καταδεικνύει ότι η μέτρηση και επαλήθευση δεν συνδέονται αυστηρά με τη φάση λειτουργίας του έργου αλλά αποτελούν αναπόσπαστο μέρος της διαχείρισης και ανάπτυξης του έργου, συνοδευόμενο από έλεγχο ποιότητας σε κάθε βήμα. Το προτεινόμενο πλαίσιο μπορεί να είναι χρήσιμο για τους Υπεύθυνους Διαχείρισης έργων για την ενσωμάτωση των διαδικασιών μέτρησης και επαλήθευσης στη διαχείριση του έργου καθώς και την εναρμόνιση των διαδικασιών με τα στάδια ανάπτυξης του έργου σε μια ολοκληρωμένη διαδικασία σχεδιασμού και εκτέλεσης έργου.

Τα δεδομένα μετρηθείσας ενεργειακής απόδοσης που έχουν ληφθεί από το πρώτο έτος μέτρησης και επαλήθευσης μιας πιλοτικής γειτονιάς μηδενικής ενεργειακής κατανάλωσης δείχνουν ότι οι έχουν επιτευχθεί οι στόχοι για παραγωγή ανανεώσιμης ενέργειας τουλάχιστον 50 kWh/m^2/έτος σε επίπεδο γειτονιάς και μέγιστο 20 kWh/m^2/έτος καθαρής ρυθμιζόμενης κατανάλωσης ενέργειας σε επίπεδο κτηρίου. Αυτά τα αποτελέσματα έχουν προκύψει μέσω μιας ολοκληρωμένης προσέγγισης για το σχεδιασμό, την κατασκευή και την παρακολούθηση της γειτονιάς, με κόστος επένδυσης 24% χαμηλότερο από το κόστος επένδυσης για ένα μεμονωμένο κτίριο μηδενικής ενεργειακής κατανάλωσης παρόμοιας απόδοσης. Ωστόσο, έχει εντοπιστεί και μια μη αμελητέα απόκλιση απόδοσης που προκαλείται από τους κατοίκους.

Εξετάζοντας τη συνολική κατανάλωση και την παραγωγή των φωτοβολταϊκών της πιλοτικής γειτονιάς, τους πρώτους πέντε μήνες παρακολούθησης έχει επιτευχθεί θετική ισορροπία. Συνολικά, η γειτονιά έχει επιτύχει ένα θετικό ενεργειακό ισοζύγιο σε ετήσια βάση για τις ρυθμιζόμενες ενεργειακές της ανάγκες. Οι τεχνολογίες παραγωγής ανανεώσιμων πηγών ενέργειας είναι απαραίτητες για τις κοινότητες μηδενικής ενέργειας, αλλά συχνά η παραγωγή δεν συμβαδίζει με τη ζήτηση. Η πρόβλεψη επιτρέπει το σχεδιασμό και την εφαρμογή προγραμμάτων διαχείρισης ανάλογα με την αναμενόμενη παραγωγή, βοηθώντας έτσι στην αποτελεσματικότερη και έξυπνη λειτουργία. Η ανάπτυξη τεχνητών νευρωνικών δικτύων έχει αποδειχθεί αποτελεσματική για την πρόβλεψη της παραγωγής 24 ώρες μπροστά.

Κοινό σημείο αναφοράς για όλα τα θέματα είναι ο ρόλος των χρηστών. Οι χρήστες χρειάζεται να συμμετέχουν ως ενδιαφερόμενα μέρη σε μια ολοκληρωμένη διαδικασία σχεδιασμού και παράδοσης έργου. Η κατανόηση των αναγκών, των προσδοκιών και της συμπεριφοράς τους είναι ουσιαστικής σημασίας για τον αποτελεσματικό σχεδιασμό, αξιολόγηση και διαχείριση μηδενικής ενεργειακής κατανάλωσης και έξυπνων κτηρίων ή κοινοτήτων.

ABSTRACT

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. Expanding the zero energy scale from buildings to communities offers the potential of overcoming the limitations of single buildings related to building use, size, on-site renewable energy availability and cost.

In order to achieve the green, sustainable, zero energy performance aspirations, building design is undergoing a paradigm shift with the introduction of the Integrated Design Process (IDP). The IDP is an iterative process that requires involvement and collaboration of various professionals from the start of a project.

For the design and operation of high performing, zero energy buildings and communities, measurement and verification (M&V) of performance is identified as a crucial task. As a result, a vast amount of data is available through monitoring equipment and sensors that form an interconnected, interoperable network of knowledge. This knowledge coupled with the power of Artificial Intelligence (AI) makes the built environment smart.

The literature so far on zero energy communities is mainly theoretical, in that it does not present experience from realised projects. This work contributes by presenting the integrated approach that has been implemented in four pilot zero energy neighbourhoods (ZEN), as well as the lessons learned from its implementation. The experience gained through the integrated approach to design, construction, and monitoring of the four pilot ZEN revealed two main issues: 1) the external barriers that are raised by the planning policies and regulations; and 2) the challenge of managing and integrating the needs and requirements of multiple project stakeholders.

To overcome these barriers while securing the benefits of the approach, the management of such projects needs to focus from the outset on the establishment of a project management structure that will ensure the coordination and integration of the various stakeholders. The use of a standardized collaboration protocol from the preliminary design stage is recommended to facilitate future projects. In addition regulations need to be updated towards facilitating zero energy community project implementation.

Currently, there is limited application of rigorous M&V procedures in the design, delivery and operation of low/zero energy dwellings and communities. Focusing on the M&V that has been designed and implemented in the four pilots, it has incorporated guidance from existing protocols, linked to the project development phases, and populated with lessons learned through implementation. The resulting framework demonstrates that M&V is not strictly linked to the operational phase of a project but is rather an integral part of the project management and development, accompanied by quality control in every step. The proposed framework can be useful to project managers for integrating M&V into the project management and explicitly aligning it with the project development stages into an Integrated Design and Delivery process.

The measured performance data that have been obtained from the first M&V year of a pilot zero energy neighbourhood reveal that the design targets for at least 50 kWh/m^2/year RES production at neighbourhood level and maximum 20 kWh/m^2/year of net regulated energy consumption at building level have been achieved. These results have been obtained through an integrated approach to design, construction and monitoring for the neighbourhood, with investment cost 24% lower than the investment cost for a single zero energy building (ZEB) of similar performance. Nevertheless, a non-negligible performance gap caused by occupants has been identified.

When considering the total consumption and PV production of the pilot ZEN, the first five months of monitoring starting from the beginning of summer, it has achieved a positive balance. Overall, the neighbourhood has achieved a positive energy balance on a yearly basis for its regulated energy needs. Renewable energy production technologies are indispensable to the zero energy communities, but often production does not match demand. Forecasting allows the design and implementation of management schedules depending on expected production and demand, thus assisting towards more efficient and smart operation. The development of artificial neural networks (ANN) has been proved effective towards production forecasting 24h ahead.

Common theme for discussion for all topics has been the role of humans, either as occupants or users or citizens. Humans need to be involved as stakeholders within an integrated design and project delivery process. Understanding of their needs, expectations and behaviour is critical for effectively designing, evaluating and managing the zero energy and smart building or community projects.

PUBLICATIONS

Journal Articles linked to the PhD:

1. Mavrigiannaki A., Kampelis N., Kolokotsa D., Marchegiani D., Standardi L., Isidori D., Cristalli C., **2017**, *Development and testing of a micro-grid excess power production forecasting algorithms*, Energy Procedia, vol. 134, pp 654-663

2. Mavrigiannaki A., Pignatta G., Assimakopoulos M., Isaac M., Gupta R., Kolokotsa D., Laskari M., Saliari M, Meir I.A., Isaac S., **2020**, *Examining the benefits and barriers for the implementation of net zero energy settlements,* Energy and Buildings, vol. 230, 110564

3. Mavrigiannaki A., Gobakis K., Kolokotsa D., Kalaitzakis K., Pisello A.L., Piselli C., Gupta R., Gregg M., Laskari M., Saliari M., Assimakopoulos M., Synnefa A., **2020**, *Measurement and Verification of Zero Energy Settlements: Lessons Learned from Four Pilot Cases in Europe,* Sustainability, 12(22), 9783

Conference Proceedings linked to the PhD:

1. Mavrigiannaki A., Gobakis K., Kolokotsa D., Kalaitzakis K., **2019**, *An Integrated Design Approach for Planning the Measurement and Verification of Zero Energy Settlements*, IAPE 19 Conference Proceedings

2. Mavrigiannaki A., Kolokotsa D., Kampelis N., Paredes F., Venezia L., Montagnino F., **2019**, *Development of ANN algorithms for forecastimg Fresnel thermal power production*, IAPE 19 Conference Proceedings

Journal Article linked to the PhD, in submission process:

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Other publications:

<u>Journals:</u>

1. Gobakis, K., Mavrigiannaki, A., Kalaitzakis, K., Kolokotsa, D.-D., **2017**. *Design and development of a Web based GIS platform for zero energy settlements monitoring*. Energy Procedia 134, 48–60

2. Kolokotsa, D, Kampelis, N, Mavrigiannaki, A, et al. *On the integration of the energy storage in smart grids: Technologies and applications*. Energy Storage. **2019**; 1:e50.

<u>Conferences:</u>

E.Tsekeri, Angeliki Mavrigiannaki, K. Gobakis D. Xilas, D. Kolokotsa, M. Kolokotroni, Francisco José Sánchez de la Flor, *On the Impact of Highly Refletive Materials on Thermal Comfort and Energy Efficiency*. Conference "IAQ 2020: Indoor Environmental Quality Performance Approaches Transitioning from IAQ to IEQ", Athens, 41st AIVC - ASHRAE IAQ, 14-16 September 2020.

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1 INTRODUCTION

1.1 Context and aim

The built-environment, including the buildings and infrastructure that form the smaller (e.g. villages) or bigger (e.g. cities) human settlements and the networks (transportation, energy, communication) that connect them, has been in the center of sustainability action plans that have been devised on European [1] as well as on International level [2], targeting the evolving climate change, environmental degradation and resource depletion.

It has been long-established that the built environment is resource and energy intensive, as well as highly polluting [3]. These characteristics are intensified by increased urbanisation; effectively requiring cities to transform their consumption, production and organisational patterns so as to be liveable and sustainable [4]. Therefore a mission is inroads towards transforming cities into green, zero or even positive energy, smart hubs. Such transformation can be achieved not least by targeting energy conservation and clean energy use from the building to the city scale.

Globally, building codes and standards have been established towards improving the performance of buildings, targeting zero energy levels [3,5]. Transitioning from the building to the city level, zero energy districts [6], eco-districts [7], green neighborhoods [8], positive energy blocks [9], positive energy districts [10] have been approached in defining the aspects of future urban sustainability. Current literature includes mostly theoretical studies for the creation of zero energy communities and rare results from implemented cases.

The creation of the sustainable built-environment can best be achieved through a revised approach to design and construction [11] which has been identified under the term Integrated Design Process (IDP) [12]. The IDP targets design and performance optimisation via iterations throughout the design, construction and in-use stages, implying new forms of project management and collaboration. There is currently room for exploration and experience to be gained through implementation of the IDP in order to better understand how actors are linked to activities, and collect evidence in its strengths and weaknesses so as to ultimately harness its full potential, especially in relation to zero energy community projects.

A critical step of the IDP is in-use monitoring. Monitoring is essential for measuring, evaluating and verifying actual performance, as well as for performance management. The above is made possible through the use and processing of data that are acquired through monitoring [13]. However, current literature lacks a comprehensive methodology for measurement and verification of buildings and communities, linked to the IDP.

Besides, when exploiting measured data for energy forecasting and control, smart energy management is introduced, enabling the transition from traditional energy grids to smart grids [14]. Such transition is of particular interest when considering the requirement for clean energy, energy efficiency and cost-efficient energy management that can be supported by smart operations [15], [14].Extended and specialised technical knowledge exists for all the aforementioned topics and literature is growing.

Herein their **potentialities and synergies are explored through real case studies that are seen as an opportunity to learn by implementation** and seek answers on the following research questions:

Research Question 1: How the IDP can be implemented for creating Zero Energy Communities? What lessons can be learned through the implementation of an integrated design, construction and monitoring approach on realized cases? What stakeholder roles and interactions can be identified?

Research Question 2: How Measurement and Verification of Zero Energy Communities is planned and executed? Where the M&V planning and execution is placed in relation to an integrated project design and delivery?

Research Question 3: What are the M&V results of a Zero Energy Neighborhood that is designed, constructed and monitored after an integrated project design and delivery process?

Research Question 4: How is smartness introduced in the integrated design of zero energy buildings and communities? How can Artificial Intelligence support smart energy management of zero energy buildings and communities?

1.2 Significance

The significance of the thesis lies in the fact that it **concurrently investigates and brings together state of the art concepts and practices that have not been identified in a common framework before.** Furthermore, the thesis answers the research questions by analysing **real case studies**.

Through the **implementation of Integrated and Smart design aspects on buildings and complexes that are designed and constructed with zero energy performance targets**, the thesis aims to **identify the links that connect and place these concepts in a holistic action framework for the creation of zero energy and smart buildings and communities**. As a result, the knowledge obtained from the research will contribute to the formulation and expansion of a solid ground for future implementation of zero energy and smart communities, through systematic integrated design, construction, measuring and managing processes that ultimately serve the sustainability visions.

1.3 Thesis structure

Following the introduction, section 2 provides the background on the major topics of the present thesis. First, the background on the zero energy concept is given with specific focus on the state of the art for zero energy communities. Next the IDP is reviewed. The Measurement and Verification (M&V), prerequisite for operating and maintaining high performance buildings, is reviewed next. Finally, the background closes with the rise of the smart built environment that occurs along the development of the previously discussed topics.

The research methodology is explained and diagrammatically presented in section 3.

Section 4 investigates the implementation of an integrated design approach in four pilot zero energy neighbourhoods (ZEN). This involves the structure and steps of the approach, the stakeholders linked to this process, as well as identified barriers and drivers that result from experience of these pilots. The section closes with a discussion that synthesises the main outcomes and observations that result from the aforementioned analysis.

In section 5 the integrated framework that has been developed for measurement and verification of zero energy neighbourhoods, is presented. The links and relation of the framework with the integrated design process for ZEN are discussed.

Section 6 focuses on the actual measured results obtained from a ZEN. The section includes quality evaluation of the collected data as well as evaluation of the actual energy performance of the neighbourhood. A discussion on the results closes the section, where links with observations discussed in the previous section are identified.

In section 7, the smart component of the design is investigated. This involves two case studies where the application of Artificial Intelligence with Artificial Neural Networks (ANN) is investigated. The purpose is to develop ANN algorithms that can effectively predict production 24h ahead.

The thesis concludes in section 8. The main outcomes and future research paths are highlighted and limitations are recognised.

2 BACKGROUND

2.1 The era of zero energy buildings and zero energy communities

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[16]. In fact, the zero energy concept is in the centre of policies worldwide being already in effect [16], since improving the performance of buildings, ideally to zero energy levels, is vital for the accomplishment of the long-term sustainability goals [17]. 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 [18]. The beginning of 2020 marked officially the era of ZEBs worldwide (Figure 1).

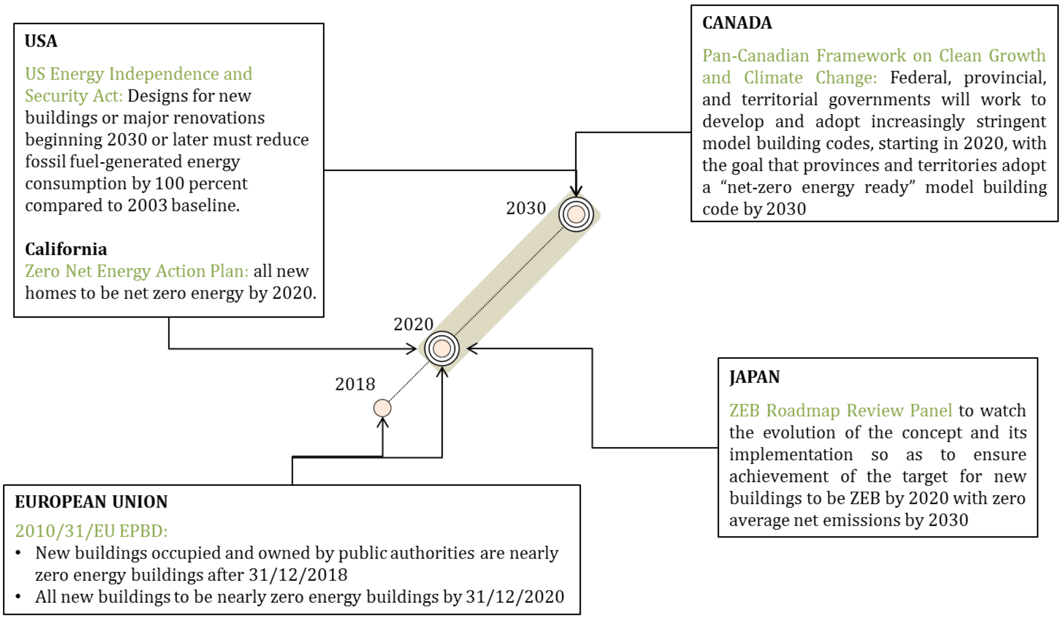


Figure 1: ZEB policies and initiatives (according to information recorded in [16]**).**

In Europe, the requirement for all new buildings to be nearly zero-energy buildings (NZEB) from 2020 was introduced with the 2010/31/EU Directive on the Energy Performance of Buildings (EPBD) [19]. California state has also set a goal for residential and commercial buildings to be ZEB by 2020 and 2030, respectively, and has adopted a Zero Net Energy Action Plan to ensure achievement of these targets [16]. The Japanese Ministry of Economy, Trade and Industry defines ZEB as *"a building whose annual net consumption of primary energy is zero"* and has set up the ZEB Roadmap Review Panel to watch the evolution of the concept and its implementation so as to ensure achievement of the target for new buildings to be ZEB by 2020 with zero average net emissions by 2030 [20].

According to the EPBD, a nearly zero energy building has very high performance and its very low energy demand is covered by renewable energy sources (RES) that are available on-site or nearby. In the scope of the EPBD, heating, cooling and domestic hot water (DHW) needs are principally considered for determining the performance [19]. Up until 2015, the NZEB performance definition has had a slow uptake in the EU member states and with discrepancies in the primary energy consumption targets [21]. The United States Department of Energy defines ZEB as *"an energy-efficient building where, on a source energy basis, the actual annual delivered energy is less than or equal to the on-site renewable exported energy"* [22]. The definition of the zero energy building has been under discourse in literature, since it can be differentiated depending on the selected physical boundary, the metrics of the balance, the period of balance and the energy uses accounted for in the balance [23,24].

As zero energy buildings assume the adoption of RES, the selection of RES affects the achievement of the zero energy goals [25]. Aeolic energy is limited by wind regimes on-site and might be more difficult to incorporate in urban environments. Geothermal energy, which is weather independent, can be produced by geothermal power plants installed in urban areas [26]. Biomass is imported to the site, so does not fall within a definition that accounts for on-site renewable production. Photovoltaic (PV) is the most widely adopted RES in zero energy buildings [27,28]. PV production depends on orientation and can be limited by shadowing effects that might occur in densely built areas. The size of the building and available roof area determine the extent that electric loads can be covered by PV production [29]. Building use is also a determining factor in the achievement of the zero energy balance where residential buildings can achieve a positive balance whereas commercial buildings can reach the balance after the extended adoption of RES [27]. Focusing on commercial buildings, depending on the approach used to calculate the balance, it might be more difficult for certain building sizes to achieve zero energy [30].

Besides, the initial investment cost remains a challenge. On this topic, researchers have investigated cost-optimal solutions for ZEBs [31–33]. Though a cost-optimal solution could be achieved, in some cases this was at an energy performance level far from the high-efficiency level expected for ZEBs [32,33]. Higher performance levels could only be achieved with higher investment costs [32]. In order to be cost-effective, ZEB design and detailing should reduce energy demand to a minimum. The remaining energy demand can then be supplied by RES [34]. Costs also depend on parameters such as the climate, which affect renewable energy generation potential and building energy performance. In certain climates, the life cycle cost (LCC) of ZEBs can be higher than the baseline [35]

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, renewable energy availability on-site and costs [25,28,29,36,37]. Therefore, despite lacking one shared and acknowledged definition and calculation approach [16,23,24,38,39], the zero energy concept has intrigued researchers to investigate its applicability on a bigger scale, usually the scale of a sub-section of a city.

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 [40,41]. Cities hold an undeniable potential in the transformation of the energy use landscape and as the zero energy concept presupposes the integration of 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 [42,43].

2.1.1 Zero energy beyond single buildings: state of the art

Similarly to ZEBs, the net zero energy communities have very low energy needs that can be covered by RES. 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"* [44]. The United States Department of Energy defines the zero-energy community similarly to the zero energy building 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) [19] 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"* [45]. 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"* [6].

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 [25,45,46]. The results in [47] 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 [48].

Both existing areas [25,37,55,56,42,47,49–54], as well as new developments [48,49,65,66,57–64], have been studied for their potential to become zero energy. 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. 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) [6,25,44,45,50,51]. Most studies investigate zero energy communities focusing on the building-related energy component, either comprising various types of buildings [52,54,57–59,64,66–68], or only residential [37,42,65,69,47–49,55,56,60,62,63].

Ascione et al. [59] 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 [45].

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 [53,54,71,58,61,63,65,67–70]. 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 [69]. Kim et al. performed a techno-economic analysis and sizing study of a district heating and renewable energy system for a mixed-use net zero energy community in South Korea [58]. The optimal sizing and techno-economic feasibility of a PV power plant for a rural community in Pakistan is presented by Rafique et al [53]. Both studies conclude that economically viable solutions exist that can also offer significant emissions reduction. A multiple-criteria decision framework has also been proposed for supporting decision making during the planning of a RES system for a zero energy community [71].

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 [55]. 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 [66]. The capital costs for building retrofit to near zero energy building levels have been calculated to be 198% higher than the business as usual retrofit, while using a neighborhood approach the capital costs are reduced by 16.8% compared to capital costs for single buildings [49].

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 [57]. 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 [49].

Performance targets are scarcely presented in literature and when set they are in relation to the research scope. In [58], 44.7 kWh/m2/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 [62].

The measured average energy consumption (April-December 2013) of the net zero energy development West Village in California was 3.1 kWh/m2/month regulated energy use and 5.8 kWh/m2/month total energy use [72]. In [61], 80% of the primary energy needs are met by renewable energy sources, according to simulation results, and in [51] up to 91% global energy consumption reduction is calculated that can be achieved when transforming neighbourhoods to become zero energy, depending on the retrofit scenario chosen. Finally, in [64] 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.

Various terms have been used to discuss the implementation of the zero energy concept beyond the single building scale, 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 [25,45,50]. 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 [45,50]. Similarly in [73], 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 [45,73]. In fact, these interactions can influence the achievement of the zero energy goals [37].

Mittal et al. studied the potential of a community to achieve zero energy through consumers' participation in a community solar program. By simulating various scenarios of RES, in varying pricing options and varying community interactions, the researchers concluded that the development of community thinking, through increased interactions is key and can lead to high levels of electricity covered by RES adoption within the community. Furthermore, it was highlighted that many stakeholders need to get coordinated and support the adoption of policies that allow the implementation of community solutions [37].

2.2 The Integrated Design Process

Applying energy conscious design strategies, incorporating innovative energy technologies and implementing energy monitoring and management are the means to create zero energy buildings and communities on the road to sustainability. The design and construction process inevitably fall under revision and the key concept that characterizes the new approach to design and construction is **integration** [11,74,75]. The Integrated Design Process (IDP) has gained attention as sustainable building practices and the green, low–energy and recently zero energy building concepts evolved [11,74,76–78]. The details, benefits, weaknesses and elaboration of the process have been suggested to be subject of research and development for the IDP [79]. Literature has focused on these topics with the aim to assist the building industry through this paradigm shift in building design. As a result, the characteristics and steps of the process have been a subject for investigation.

Through practice, collection of data from case study buildings and interviews with building design and construction professionals it has been recognized that sustainable building design demonstrates a design approach where considerable design effort is transferred to the beginning of a project with the collaboration of various building practitioners that share their expertise and set a comprehensive design basis on which the project will evolve and will be optimized [76,80]. Various projects and organizations have worked towards the formulation of a clearly defined process [12,81–84].

In [81] is given a comprehensive roadmap of the process. The drivers and the principles of the process are analyzed and detailed guidance step by step for successfully implementing IDP is presented supported by relevant case studies. The IEA Task 23 also provides a comprehensive guide for implementing IDP that is supported by a navigator tool [12]. Interviews with industry professionals and consultation with experts assisted the development of the Guide to Integrated Design and Delivery document where specific attention is also given to the contractual requirements of the process [83]. On the same path the American Institute of Architects has developed a guide to Integrated Project Delivery, similar to the previously mentioned works, it comprises all stages from project conceptualization to delivery [82].

Table 1: The steps of the integrated design process

<table>
<tr><th>[81]</th><th>[12]</th><th>[83]</th><th>[82]</th><th>[84]</th></tr>
<tr><td rowspan="2">Pre-design</td><td>Basics</td><td>Kick-off</td><td rowspan="2">Extended Programming</td><td>Basics
(steps 1 - 3)</td></tr>
<tr><td>Pre-design</td><td>Pre-design</td><td>Pre-design
(steps 4 & 5)</td></tr>
<tr><td>Schematic</td><td>Concept design</td><td>Schematic</td><td>Criteria design</td><td>Concept design
(step 6)</td></tr>
<tr><td>Design development</td><td rowspan="2">Design development</td><td rowspan="2">Design development</td><td>Detailed design</td><td rowspan="2">Design development
(steps 7 – 14)</td></tr>
<tr><td>Construction documentation</td><td>Construction documents</td></tr>
<tr><td rowspan="2">Bidding-construction-commissioning</td><td rowspan="2">Construction</td><td rowspan="4">Construction and operation</td><td rowspan="2">Construction</td><td>Construction
(steps 15 – 17)</td></tr>
<tr><td>Commissioning (step 18)</td></tr>
<tr><td>Building operation (startup)</td><td rowspan="2">Operation</td><td rowspan="2">Closeout</td><td rowspan="2">Operation
(steps 19 & 20)</td></tr>
<tr><td>Post-occupancy</td></tr>
</table>

In Table 1 the steps for implementing an IDP, as these have been suggested in the aforementioned guides, are tabulated. Although the number or naming of steps may vary, the actions related to the process are common.

Implementation of integrated project design and delivery requires a diverse team of professionals that will collaborate from the beginning of the project [12,81–83]**.** Purpose of the initial meeting between the team and the client is the definition of the project's aspirations, the identification of potentialities or problems and goal setting. The assembly of the team and meeting with the client in order to set the launching base of the project are the actions that compose the first step that kicks off the process [12,82–84]. This step is characterized as basics in [12], "kick-off" in [83]. The following step, characterized as "pre-design" includes exploration of design strategies and identification of synergies for producing a refined energy and sustainability targets' plan for the project [12,83,84]**.**

The aforementioned two steps, are identified as one "pre-design" step in [81] and "extended programming" in [82]**.** The pre-design decisions, taken in one or two steps, form the basis upon which the "schematic" or "concept design" is built. Design alternatives are evaluated while design strategies and targets are re-evaluated and become more concrete [12,81–84]. The schematic design that will result from this process is further developed at the next step, the "design development". This step may include a number of iteration loops where the design choices, the energy strategies and combined performance of all systems are evaluated and optimized [12,81,84] before moving to the "construction" step. The construction step also involves the commissioning process [81]**,** [12]**,** [82]. In [83] construction has been grouped with "operation" as one step.

Contrary to the conventional process, where the project ends after completion of construction, the IDP continues into the "operation" or "post-occupancy" phase [12,81,83,84]**.** The operation phase includes ψ [81]**,** [78]. In [85], presenting a case study middle school designed to achieve net-zero energy, the measurement and verification of the intent is documented as critical integrated design practice. Although operation is the final step its successful implementation in support of a project's M&V requires preparation and planning from the beginning of the project which is documented in an M&V Plan for the project [86], [87].

In [82], the final step is named "closeout", but it foresees the existences of a fully developed "as-built" building information model (BIM) that can be used for monitoring, control, security and performance evaluation so as to support long-term building management, maintenance and operation. The employment of BIM technical solutions has been widely recognized in IDP related literature as enabler to the process [74,82,88,89]. Integration of BIM in the process has been discussed along the new forms of collaboration that emerge and the related contractual implications [89], [88], .

The transition from the traditional design and construction process to the Integrated Design Process and Integrated Project Delivery calls for new forms of stakeholder collaboration and new forms of project management and contractual agreement [12,83,89]. The traditional approach to design and construction management with the use of traditional design-bid-build contracts, is characterized by fragmentation, where various BD+C professionals are introduced at different stages and probably are working on separate goals [90], [91]. This fragmentation also hinders the project's quality management[91]. On the contrary, IDP assisted by BIM solutions, is emphasizing on close collaboration and alignment of all involved stakeholders from the early planning stages and throughout design and execution, in order to achieve optimum design and performance results with optimum time and cost management [12], [83].

Researchers have also investigated tools and methodologies that can assist the integrated design process in decision making. In [92] is developed a method for simultaneous assessment of thermal, visual and air quality autonomy as part of an integrated process design stage analysis. Chardon et al. investigated the development of a BIM compatible tool to serve decision making for optimization between costs and performance of the building envelope. The authors suggest that this tool can support integrated design of small scale projects and propose that more design criteria, including primary energy consumption, thermal comfort and life cycle analysis can be included in the decision making tool [93].

Table 2 summarizes the attributes of the IDP. Despite being defined in its steps and attributes, there is still room for exploration and experience to be gained through implementation of the IDP in order to better understand how actors are linked to activities and how to handle costing and contracts [94]. Wider implementation of the process can also provide evidence in its strengths and weaknesses so as to ultimately harness its full potential in creating sustainable constructions [95]. In view of the collaborative form that the IDP implies, familiarization with the process, the underlying concepts of integration and the supporting tools, need to become part of the educational curriculum, especially for architects that are often identified as leaders in this collaborative form [94], [96].

Table 2: The IDP attributes that have been identified in the reviewed literature

IDP attributes	References
Inclusive	[12,74,76,78,79,81–84,89]
Iterative	[11,12,80,81,84]
Holistic thinking	[11,12,74,78,81,84]
Broad team/Interdisciplinary	[12,74,89,76,78–84]
Collaborative	[12,74,89,76,78–84]
Goal -driven	[11,12,78,81–84]
Front loaded	[12,74,79–83]
Systematic	[12,81–84]
Optimised	[12,78,81–84]

2.3 Measurement and Verification: an overview of drivers and trends

For design and operation of the highly energy-performing and efficient built environment, measurement, and verification (M&V) of performance is identified as a crucial task. Continuous performance monitoring is integral to the IDP. In addition, implementation of M&V is a prerequisite within the European Union's Energy Efficiency Directive [95]. Continuous monitoring and verification of performance is also emphasized in the Energy Performance of Buildings Directive (EPBD) [96]. International green building standards (e.g., LEED – Leadership in Energy and Environmental Design), prescribe a series of basic (prerequisite) and advanced (extra credits) procedures, intending to set up a feedback mechanism on building energy use trends, performance assessment, and consequent measures for improved efficiency [97].

M&V encompasses the implementation of processes for measuring the energy performance of systems, technologies, and/or strategies linked to building energy consumption and efficiency and verifying performance against expected targets. Inherently, M&V presupposes the use of monitoring equipment and energy-saving calculations [97]. The reliability of the M&V depends on the design and implementation of a reliable monitoring scheme and on coordinated planning of all actions that should be performed for measuring, evaluating, and verifying performance. This is a complicated process to begin with, but supported through well-established protocols —

the more prominent being the International Measurement and Verification Protocol (IPMVP) [86] and the ASHRAE Guideline 14 [87].

The IPMVP sets the principles, terminology, and standard practices for M&V and has been developed to provide a robust basis for the assessment of savings from energy efficiency, water efficiency, demand management and renewable energy programs [86]. ASHRAE Guideline 14 offers technical guidance on M&V; it addresses M&V of retrofitted Energy Conservation Measures (ECM) explicitly and provides detailed guidelines on the calculation of savings, uncertainty evaluation, instrumentation selection and calibration, as well as data management. ASHRAE Guideline 14 was developed to support the energy services companies (ESCOs) in their transactions with clients and energy utilities [87].

These protocols have been created with the initial purpose of providing a basis for the evaluation of energy-saving programs by listing standard M&V procedures and calculation methods. However their instructions are also applicable to new built projects. Given the ZEB rise, a measurement and verification protocol specifically for net-ZEB has been produced. This protocol's motivation rose from the need to provide a structured proposal for measuring and verifying the net-ZEB status considering the lack of a universally accepted definition. In this protocol, the steps for planning, installing, and operating a net-ZEB monitoring system are presented. The document addresses strategies for monitoring energy and Indoor Environmental Quality (IEQ) as well as data post-processing procedures [98].

Monitoring is indispensable for tracking and effectively improving the implementation of the zero energy concept [24,36,72,98–100]. 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 [52,72,101,102]. 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 [103,104]. Through measuring and analysing actual performance, data can be fed back into simulation models allowing the quantification and evaluation of the performance gap [103], as well as the identification of causes and consequent mitigating actions [105], [104] such as lack of precision in the definition of realistic boundary conditions at building and settlement level [46].

The performance gap is a strong driver for performing M&V [106] and the availability of real data from monitoring allows for a sound assessment of the performance gap [103]. The measured performance also provides feedback to occupants, thus assisting the transition of occupant behaviour to an energy-conscious mind-set and enhancing the success of the applied energy strategies and further assisting in closing the performance gap [107]. In particular, performance monitoring can be exploited to develop real-time and feed-forward information strategies to drive more rational energy-related occupant behaviour [108], [109].

In [72], monitoring and verification of performance were intended in identifying the gap compared to design and modelling 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 [52], 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 behaviour. 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 [52].

M&V is particularly critical in performance-based contracts, where a third party contractor guarantees the performance of the implemented energy-saving measures and the installed equipment [110]. Besides, monitoring combined with building energy management and predictive controls can be further utilized towards advancing building performance [103,111]. The feedback provided through M&V feeds decisions for building energy management aiming to improve performance [13], as well as Demand Side Management (DSM) programs aiming to optimize costs and efficiency [112]. Measured performance data are the cornerstone of Building Energy Management Systems (BEMS) and have long been utilized for energy performance management [113,114].

From that point of view a link can be found with M&V2.0. M&V campaigns in literature have been associated to ECM implemented on existing buildings, primarily industrial, or office buildings, which has created an interest in developing methodologies for the creation of reliable baseline model and savings estimation, reducing uncertainties, computation time, and M&V costs [112,115–119] as well as automating the M&V [120–123]. Automation of the M&V, namely M&V 2.0, is the research focus investigating the development and potential of automated, real-time M&V.

A Cloud computing platform for the measurement and verification of energy performance in real-time was presented by Ke et al. [120]. The platform was tested on the evaluation of energy conservation in the freezer and cold storage system of a hypermarket. The authors suggested, however, that its use could be expanded for other types of buildings and energy conservation measures. Gallagher et al. have also developed a cloud computing platform to support M&V 2.0. The platform could provide real-time savings estimations with high confidence [121].

2.4 Towards a smart built environment

In the era of high performing, zero energy buildings and communities, monitoring for continuous measurement, verification, adaptation and improvement of performance has become indispensable and is introduced as a vital step in an integrated process of designing, constructing and managing the built environment. This is supported by the development of Information and Communication Technologies (ICT) that has been a driver for the rise of the smart built environment [124] accompanied by the growing Internet of Things (IoT) [125]. As a result, a vast amount of data [126], is available through monitoring equipment and sensors that form an interconnected, interoperable network of knowledge [127,128]. This knowledge coupled with the power of Artificial Intelligence (AI) [128,129] makes the built environment smart.

In response to these developments, the EU has introduced the "smart readiness indicator" aiming to measure the capacity of buildings in employing smart technologies for adapting to occupants' comfort, maintaining and optimizing their performance and interacting with the energy grid [130]. One step further, the 2020 decade has been declared to be EU's digital decade aspiring for a digital transformation by 2030. This encompasses digital transformation of skills, businesses, governance and citizenship, and infrastructure [131]. Aligned with this vision, a series of policies and initiatives aim to promote smart cities as places that supported by ICT tackle environmental, social, organizational, administrative, energy and resource pressures that challenge sustainability in a highly urbanized world [132].

The concept of the “smart city” has been distinctively studied in literature gaining popularity the past decade along the concept of the “sustainable city” [133]. The definition and description of the smart city and its assets is an ongoing discourse in recent literature. This is related to the concept of the city itself and the theoretical, historical, political, philosophical but also practical approaches on urban development processes, the function of cities and the role of citizens [134–136]. The smart city concept features smart infrastructure, open data, smart services and Apps, and an overarching smart city vision [137] aiming to enhance citizen experience, quality of life and quality of services, promoting citizen engagement, social equality and inclusion, increasing connectivity, creating and sharing knowledge, efficiently managing energy and resources, fostering digital economy and environmental sustainability [133,137,138].

The smart grid is an enabling factor to the smart cities from the energy perspective [127]. Traditional grids lack flexibility in power generation and load operation [15], whereas a smart grid comprises distributed energy sources, energy loads and storage components, forming a semi-autonomous entity with energy management capabilities [139]. Energy Management Systems (EMS) are essential component of smart grids for the purpose of their reliable and efficient operation [139], [140]. A smart grid communicates with its components and integrates intelligent energy management that controls its loads so as to achieve an efficient and cost-effective operation [15], [141,142]. In [143] an energy management algorithm is tested for optimum integration and operation of a PV array and a battery for serving a micro-grid’s loads. In [144] two algorithms are proposed and tested on an existing micro-grid, one for energy scheduling and one for demand response. Increased efficiency and occupant satisfaction has been achieved by the EMS applied in a University Campus [142].

Smart buildings are components of both the smart cities and the smart grid [127], [145]. Within the smart grid, Building Energy Management becomes part of a more comprehensive energy management system, where energy flows are regulated and optimized with the application of suitably designed controls [146], [147]. Under demand response programs, smart buildings’ interaction with the grid can be optimised, through optimum utilisation of RES and stored energy that effectively reduce peak loads and electricity costs [147], [148].

Dakheel et al. identify four basic functionalities of the smart buildings: climate response, user response, grid response, and monitoring and supervision. This functionalities lead to the four basic features of the smart buildings: near zero energy performance, energy flexibility, real-time monitoring, and real-time interaction. Resulting from these features, a series of quantitative key performance indicators (KPI) for the smart buildings can be defined in addition to the qualitative smart readiness indicator [149].

An aspect that has been stressed in the smart building and smart city literature is balancing the decision power among automation and the occupant/citizen expectations. Smart buildings aim to be adaptable and responsive to the occupants' needs [150] and therefore a level of decision power and control needs to be left to the occupants [151], [152] and in the case of cities, to the citizens [135], [136]. Different user groups might perceive differently the function and necessity of smart technologies and smart operations, therefore understanding of the users' needs and expectations is fundamental for the smart built environment to fulfill its purpose [153], [145]. Under this scope, technology acceptance, literacy and the digital divide need to be considered too for user and citizen engagement and optimum interaction with the smart infrastructure [136].

In his book "e-topia - Urban life, Jim – but not as we know it", W. J. Mitchell describes his vision of e-topias that can be created in the 21st century to replace the dated and dysfunctional urban development patterns of the 20th century. The e-topias are *"lean, green cities that work smarter, not harder".* The five design principles of e-topias are *dematerialiasation, demobilization, mass customization, intelligent operation* and *soft transformation* [154]. Employing wordplay with the words electronic and utopias, W.J. Mitchell in a few lines described in 1999 what is described today as "smart built environment", including the smart cities, smart buildings and the smart energy grid. In 2021 the e-topias are not utopias; they are very real and are leading into the future.

The smart built environment gathers real data, and utilizes them to evaluate its performance and feed informed decisions for adapting its operation with cost-efficient, energy-efficient, human comfort and environmental perspectives [128,129,150,151]. To summarize its properties, the smart built environment is **data intensive interconnected, interoperable, interactive, intelligent, and adaptable.**

3 METHODOLOGY

The methodology has been structured in steps for answering the research questions. The research design includes mixed research methods that are tailored to each research step. Each research method has been implemented with reference to case studies that have provided the basis for investigation and analysis in each step. The research design is schematically represented in Figure 2.

Step 1 – Research Question 1	
How the IDP can be implemented for creating Zero Energy Communities?	**Lessons learned** from the IDP that has been developed and implemented in 4 pilot Zero Energy Communities, as part of a EU HORIZON 2020 project: • The structure and attributes of the process • Stakeholders' Analysis
Step 2 – Research Question 2	
How Measurement and Verification of Zero Energy Communities is planned and executed?	• Mapping of the steps for M&V development and implementation in 4 pilots • Mapping of the developed M&V framework in relation to the IDP
Step 3 – Research Question 3	
What are the M&V results of a Zero Energy Neighborhood that is designed, constructed and monitored after an integrated project design and delivery process?	Data collection, analysis and evaluation from a pilot Zero Energy Neighborhood • Actual vs Simulated performance • Actual Performance vs Design Targets • Zero Energy Balance
Step 4 – Research Question 4	
How is smartness introduced in the integrated design of zero energy buildings and communities?	• Development of forecasting with Artificial Neural Networks

Figure 2: Schematic representation of the research design

3.1 Step 1 – Research Question 1: How the IDP can be implemented for creating Zero Energy Communities?

First Qualitative research has been implemented. The integrated design approach that has been developed and implemented in four pilot residential zero energy neighbourhoods as part of the Horizon 2020 ZERO-PLUS project ('Achieving Near Zero and Positive Energy Settlements in Europe using Advanced Energy Technology') [155], is subject to qualitative analysis in section 4.

The qualitative characteristics of the approach are identified and associated with the respective IDP steps and attributes that have been collected through literature review. With reference to the project management and the experience obtained from the implementation of the four pilot ZENs, the lessons learned have been captured through a series of questions that have been answered by the partners involved in the ZEN design and implementation. Three sets of questions were prepared for the three main groups: (a) Case study owners, (b) Case study support teams, and (c) Technology providers. In addition to the questionnaires, lessons learned have been supplemented through specific barriers that were encountered in the pilots, leading the partners to create an impromptu list of barriers and drivers as these have been appreciated after implementation of the pilot ZENs.

Lesson learned sessions are an opportunity to identify success stories, pitfalls and/or unintended outcomes (positive or negative) as well as recognize things that went well, things that might have been done differently, the causes of pitfalls and suggestions for facing or avoiding those [156]. Furthermore lessons learnt sessions contribute to knowledge management and establishing institutional knowledge [156], [157].

3.2 Step 2 – Research Question 2: How Measurement and Verification of Zero Energy Communities is planned and executed?

In this stage, first the steps that have been followed for the formulation of the measurement and verification framework of the four pilots are described. Following, the final framework that has been developed and implemented is presented and explained and finally its links to the overall Integrated Design Process are highlighted and discussed.

3.3 Step 3 – Research Question 3: What are the M&V results of a Zero Energy Neighborhood that is designed, constructed and monitored after an integrated project design and delivery process?

This step involves the analysis of data that have been collected from a pilot ZEN after its first year of monitoring and operation (section 6).

The energy performance evaluation of the neighbourhood follows three axes: 1. Comparison of the measured performance against the expected performance, 2. Comparison of the actual performance against the design performance targets, 3. Assessment of the zero energy balance.

The ZEN has been designed according to performance targets that have been set for both building and neighbourhood level as follows:

→ Regulated energy consumption at building level ≤ 70 kWh/m^2/year;
→ Net regulated energy consumption at building level up to 20kWh/m^2/year;
→ Renewable energy production at settlement level of at least 50kWh/m^2/year;
→ Investment costs of the buildings reduced by at least 16% compared to current costs for single ZEBs.

The following definitions apply:

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 community/settlement renewables.

Net regulated energy = Regulated energy use - Renewable energy.

The expected performance is the simulated performance according to the as-built status of the neighbourhood. Further information is provided in section 6.2.2. The expected performance per month and for the whole year is compared to measured performance and expressed in percentage (%) difference.

Furthermore, in support of the measured against expected performance evaluation, the energy signature is plotted. The energy signature is a tool that can be used as a reference and an indication of the expected consumption as well as for identifying and interpreting possible changes [158], [159]. 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 [158,160–162]. Vertical shifts of the signature indicate changes in the HVAC system such as a system upgrade [158].

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 [163]. 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 plotting and comparing the energy signatures of the actual performance against the expected performance. This approach supports the investigation of the performance gap and its relation to HVAC operation.

The zero energy balance is assessed considering the balance between RES production and residential consumption, both total and regulated. This approach is similar to the load/generation balance discussed in [24]. Although the commonly agreed temporal basis for evaluation of the zero energy balance is the annual, here also the monthly balance is calculated in support of the analysis. The following indicators are calculated for evaluating the zero energy balance:

PV production/Total consumption (%)

PV production/Regulated Consumption (%)

Self-Consumption/PV Production (%)

Self-Consumption & Battery/PV Production (%)

Self-Consumption & Battery / Total Consumption (%)

Self-Consumption & Battery / Regulated Consumption (%)

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

3.4 Step 4 – Research Question 4: How is smartness introduced in the integrated design of zero energy buildings and communities?

In the final step the introduction of smartness in the design is studied with the development and evaluation of Artificial Neural Networks (ANN). The ANN are Artificial Intelligence (AI) models with underlying principle the human brain function. Similarly to the human brain's neurons, ANNs are composed of interconnected nodes that can be trained to perform tasks.

In the present work, ANN are employed for forecasting the renewable production in two micro-grids. In the first case the objective of forecasting is the excess power of the grid and in the second case, the thermal power production.

At its simplest structure an ANN is composed of three layers of nodes: the input layer, one hidden layer and the output. The nodes of each layer are connected with nodes of the previous and following layer. Each neuron is associated with a weight value a bias value and a transfer function. Inputs are multiplied by the weight, added to bias and processed through the transfer function to provide the output. During training of the network, weights and biases are adjusted so as to give an output with the smallest error. In feed forward networks, information moves in one direction from the input to the output layer. In recurrent networks, information can also flow in the opposite direction. A recurrent dynamic network, suitable for forecasting problems is the nonlinear autoregressive network with exogenous inputs (NARX) and has been used in the present work [164].

The forecasting accuracy of the developed ANN is evaluated according to the values of Regression (R), the Mean Bias Error (MBE) and the Root Mean Square Error (RMSE).

4 INTEGRATED DESIGN PROCESS FOR ZERO ENERGY NEIGHBOURHOODS

4.1 Introduction

The literature so far on zero energy neighbourhoods is mainly theoretical, in that it does not present experience from realised projects. This section is based on the experience gained through the design, construction, and monitoring of four pilot zero energy neighbourhoods [155,165,166]. The present section contributes by presenting the integrated approach that has been developed and implemented as well as the lessons learned from its implementation.

The section offers an analysis of the stakeholders that are involved throughout design, construction and monitoring of ZENs. Through the stakeholders' analysis, the groups of stakeholders that were involved in the implementation of the approach are identified. The relation of the stakeholders to expected benefits and identified barriers is also presented.

The section closes with a discussion linking observations from the aforementioned analysed topics with reference to the new dynamics that emerge and are critical to the successful implementation of the integrated design process for zero energy neighbourhoods.

4.2 Integrated approach

The achievement of optimized energy and cost-efficient solutions for zero energy neighbourhoods requires an integrated, holistic approach to design and simulation [167]. 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 [39,168]. An integrated approach to design, construction and monitoring has been developed and implemented in four pilot neighbourhoods (Figure 3) with the aim to achieve specific energy and cost targets.

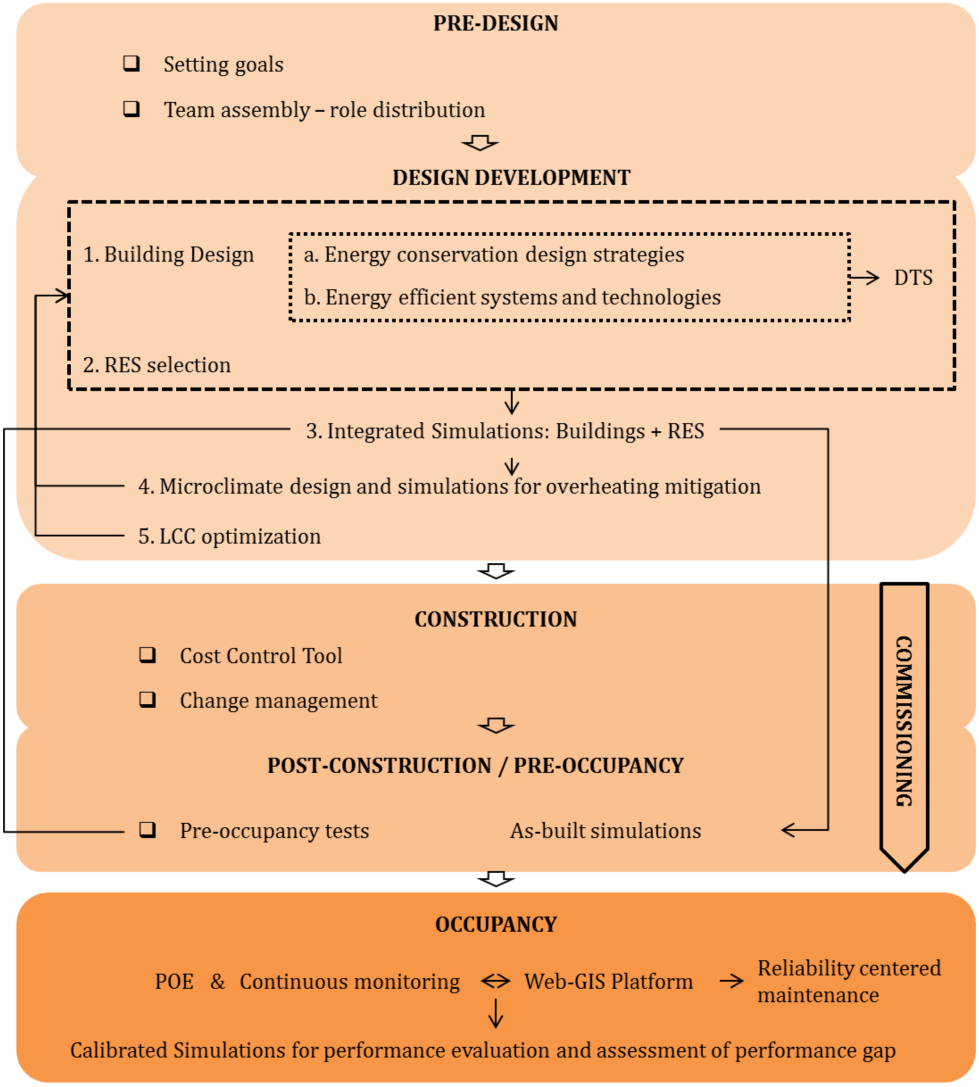


Figure 3: Design and Construction process for zero energy neighbourhoods

The structure of the approach matches the steps of the IDP starting with goal-setting and team assembly in pre-design. For the ZEN project a broad team of experts from both industry and academia, including the neighbourhood developers, has been assembled and has worked collaboratively from the beginning of the project.

Following, schematic design and design development have been supported by simulations and an optimization process through design iterations. Dynamic Thermal Simulation (DTS) tools have been employed for building performance simulation and optimization, RES performance simulation, as well as integrated building and RES simulation [155]. In addition, microclimate simulations serve the determination of performance under alternative microclimate scenarios [46]. Life Cycle Cost Analysis (LCCA) aims to minimize costs while respecting the energy performance constraints

[169], leading to the optimized design of energy and costs. The design has been reviewed and evaluated through progress meetings of the team as well as through two dedicated review workshops with the participation of external experts (as part of the activities of the Horizon 2020 project ZERO-PLUS).

A Cost Control Tool and a Change Management Tool have been developed for tracking alterations to design during construction and subsequently tracking possible changes in the performance targets [170]. 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 [171]. In addition, Post Occupancy Evaluation (POE) surveys evaluate the occupants' satisfaction and their interaction with the buildings and installed technologies [172]. 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.

The process that has been developed and implemented for the pilot ZENs possesses the attributes of the IDP (Table 3) as these have been identified in literature. It is a **goal-driven and front loaded** process, guided by specific performance targets and early effort for coordinating design aspects and decisions. It is a **holistic** thinking approach, targeting energy, microclimate, comfort, costs and lifecycle. The process is also **systematic**; constituting a roadmap of steps, processes and tools. This roadmap is not a linear process, but rather an **iterative** one, where every step is reviewed and iterated, in relation to design intentions and optimized results. **Optimization** is pursued in every step of this systematic, iterative process.

Such process has been implemented by a **broad, interdisciplinary** team of experts (from both industry and academia), including the project developers and technology experts. All experts have been **included** and worked **collaboratively** throughout the process. The team dynamics and lessons learned from the implementation of the process are discussed in section 4.3 Stakeholder Analysis.

Table 3: The IDP attributes of the ZEN approach

IDP	ZEN approach
Goal -driven	✓
Front loaded	✓
Holistic thinking	✓
Systematic	✓
Iterative	✓
Optimised	✓
Broad team/Interdisciplinary	✓
Inclusive	✓
Collaborative	✓

4.2.1 Applicability

The process has been fully implemented on 4 pilot zero energy neighbourhoods (Figure 4, Figure 5 , Figure 6, Figure 7) in 4 different European countries, representing different climatic conditions and scales of implementation (Table 4). Moreover, each case study has employed different tools depending on local context. For example the dynamic thermal simulation tool used in France, offers a module for checking the French Thermal Regulation (RT2012). Therefore is can be concluded that the process is also flexible and adaptable, applicable in varying contexts for the creation of zero energy neighbourhoods.

Figure 4: The pilot zero energy neighbourhood in UK

Figure 5: View of one of the villas in the pilot zero energy neighbourhood in Italy

Figure 6: The apartment building in the pilot zero energy neighbourhood in France

Figure 7: The demonstration prefabricated container in the pilot zero energy neighbourhood in Cyprus

Table 4: Overview of the pilot neighbourhoods where the developed Integrated Design Process has been implemented

Location	Type of buildings	Climate	Dynamic thermal simulation tool(s)
York, UK	Detached and semi-detached dwellings	Temperate	IES VE
Granarolo dell'Emilia, Italy	Villas	Temperate and Mediterranean	EnergyPlus with DesignBuilder graphical interface
Voreppe, France	Social housing apartment block	Semi-continental	Pleiades
Nicosia, Cyprus	Prefabricated container system	Mediterranean	EnergyPlus with DesignBuilder graphical interface

4.3 Stakeholder analysis

The stakeholders that were involved in the integrated design, construction and monitoring of the pilot zero energy neighbourhoods are analysed in this section and they can be divided into two main groups:

i) external stakeholders that are indirectly involved in project development,

ii) internal stakeholders, who are directly involved in project development.

4.3.1 External Stakeholders

The external stakeholders were the planning authorities and utility companies that dictated specific requirements for the approval of the submitted designs. These requirements are a result of the legislation, planning policies, and energy policies that are in place in each country and directly affect the implementation potential of design strategies and technologies (Figure 8).

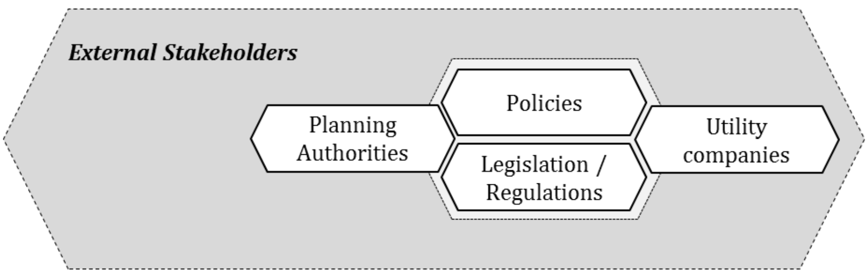


Figure 8: External Stakeholders involved in the implementation of the pilot ZENs.

The external stakeholders mainly interact during the design stages (Figure 9), when design decisions are made and permits are issued. In the 4 pilots the external stakeholders mainly affected the design development by causing changes and therefore delays in the progress of the design, and consequently delays in the start of the construction. These delays were related to the approval of the innovative technologies. The time-consuming process of obtaining certificates of conformity as well as the uncertainty of final approval led to certain technologies being excluded from the design and replaced with other market-ready technologies.

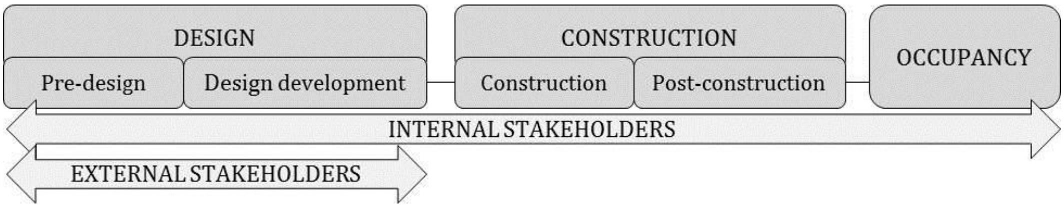


Figure 9: Involvement of external and internal stakeholders in the project phases.

4.3.2 Internal Stakeholders

The internal stakeholders were the members of the project team and were involved throughout the project phases (Figure 9). The internal stakeholders were consultants from academia (on energy, POE, monitoring, IT), technology providers (developers of innovative technologies for renewable energy generation and energy management), project owners, the design team, and the construction team. In certain case studies, the occupants were involved in the project development as well. Therefore, it has become evident that for the design, construction, and management of such projects, an expanded team is needed (Figure 10).

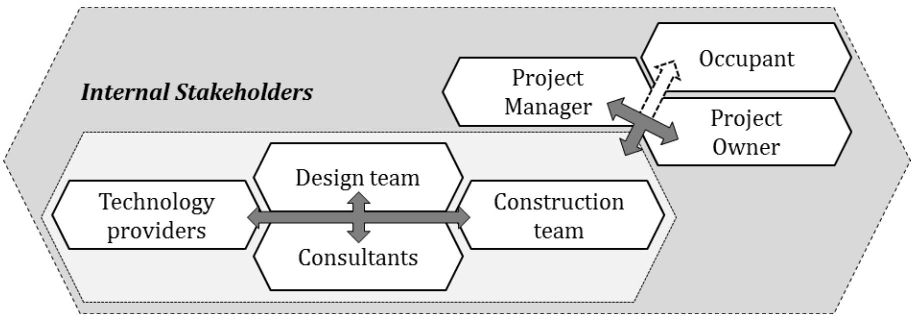


Figure 10: Internal Stakeholders involved in the implementation of the pilot ZENs.

Focusing on the involvement of the internal stakeholders in each project phase, feedback was obtained from the project partners in a structured way through the use of questionnaires. The results represent the replies obtained from the pilot ZENs in UK, Cyprus and Italy. In the pilot of France, the representative was replaced thrice throughout the project and as a result the current representative did not have a full picture of the project development.

The "level of involvement" in project phases is a number resulting from the replies to the question: *From your experience at which phase(s) needs each expert to be involved (think what you would do if you started now)? Mark all boxes that apply*. Similarly, level of involvement per communication links results from the number of replies to the question: *Which were the links of communication between the experts involved in the design of the case study? (check all that applies).* The final result represents the number of times a link was given to this expert.

First is given the "level of involvement" according to the number of project phases assigned to each expert (Figure 11). The Project owner/developer and the Energy analysis expert have the highest sum in phases of involvement, followed by the Electrical Engineer and the Technology Provider. High sum also have the IT Engineer (1^{st} in Cyprus) and the Monitoring Coordinator (1^{st} in Italy, 2^{nd} in UK). This probably results from the fact that the monitoring of the pilots and recording of data on the Web-GIS platform was a prominent task. These experts also worked with the Electrical Engineer for coordinating the design and installation of the monitoring schema with the electrical drawings.

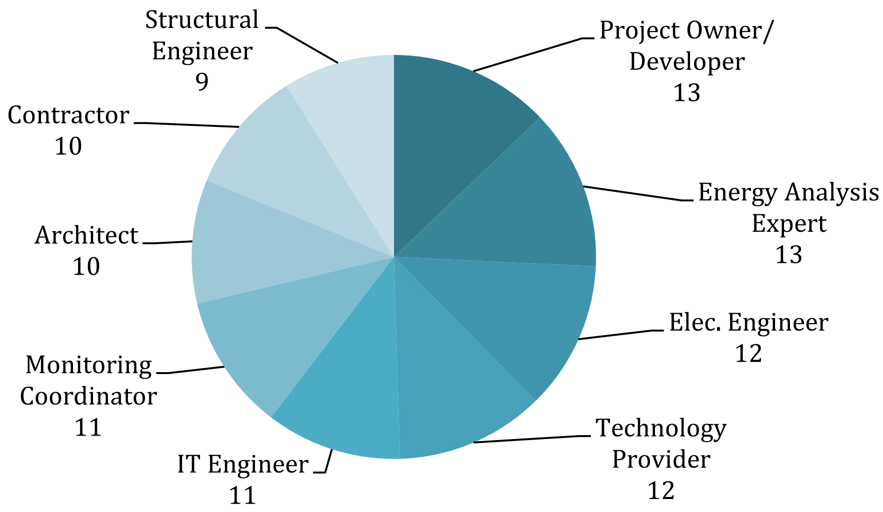


Figure 11: Level of involvement per number of phases of involvement. Each piece size is the number of times an expert was associated with either of the project phases.

The "level of involvement" per number of communication links is presented in Figure 12 for each pilot. The Project Owner/Developer has the greater sum of communication links in UK and Cyprus. In Italy, the Home Owner was involved in the process Post-Construction, replacing the Project Owner/Developer, thus the latter appears with less communication links. The combined level of involvement, including both project phases as well as communication links is represented in Figure 13. The overall level of involvement of each stakeholder in each pilot is represented by the size of the nodes, and is the result of the number of project phases in which each stakeholder was involved, and the number of communication links.

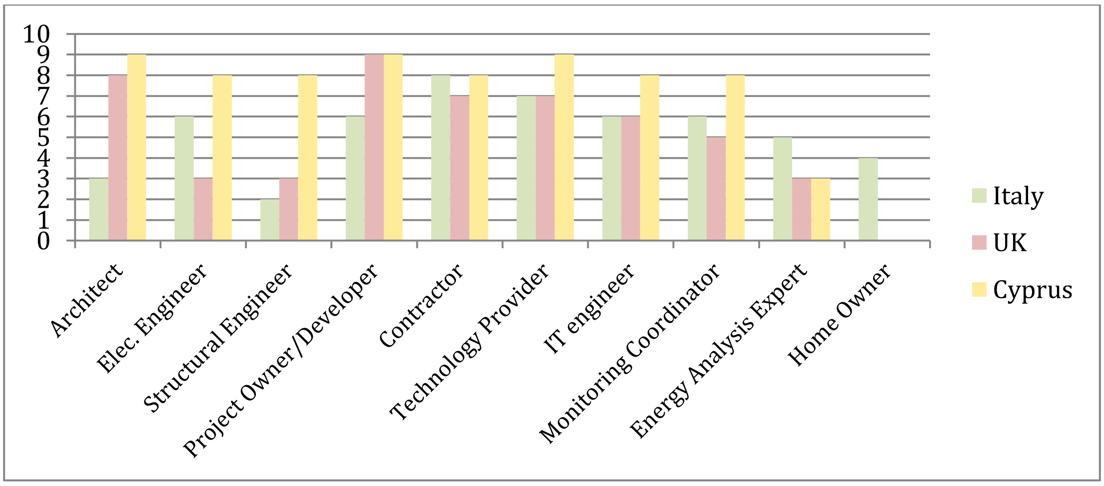
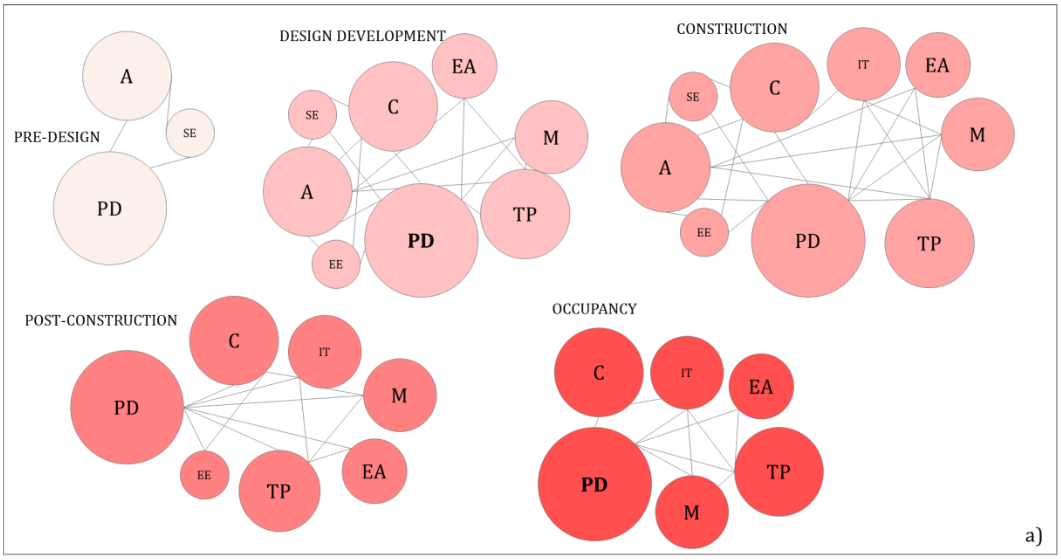


Figure 12: Number of communication links assigned to each expert in three pilots.

The mapping confirms that the internal stakeholders are almost equally involved throughout the project and that a complex network of communications is created among the internal stakeholders. In Italy, in particular, the participation of the Home Owners throughout the process was highlighted in the answers, thus allowing the placement of the Home Owners in the stakeholder mapping of the case study from Italy.

The mapping highlights the need for expanded, yet integrated, teams that work in alignment throughout the project. The coordination of such a team and of the interactions among the stakeholders is a challenging task. It should be handled by a Project Manager who has a broad overview of the project. This conclusion is addressed in more detail in the discussion.



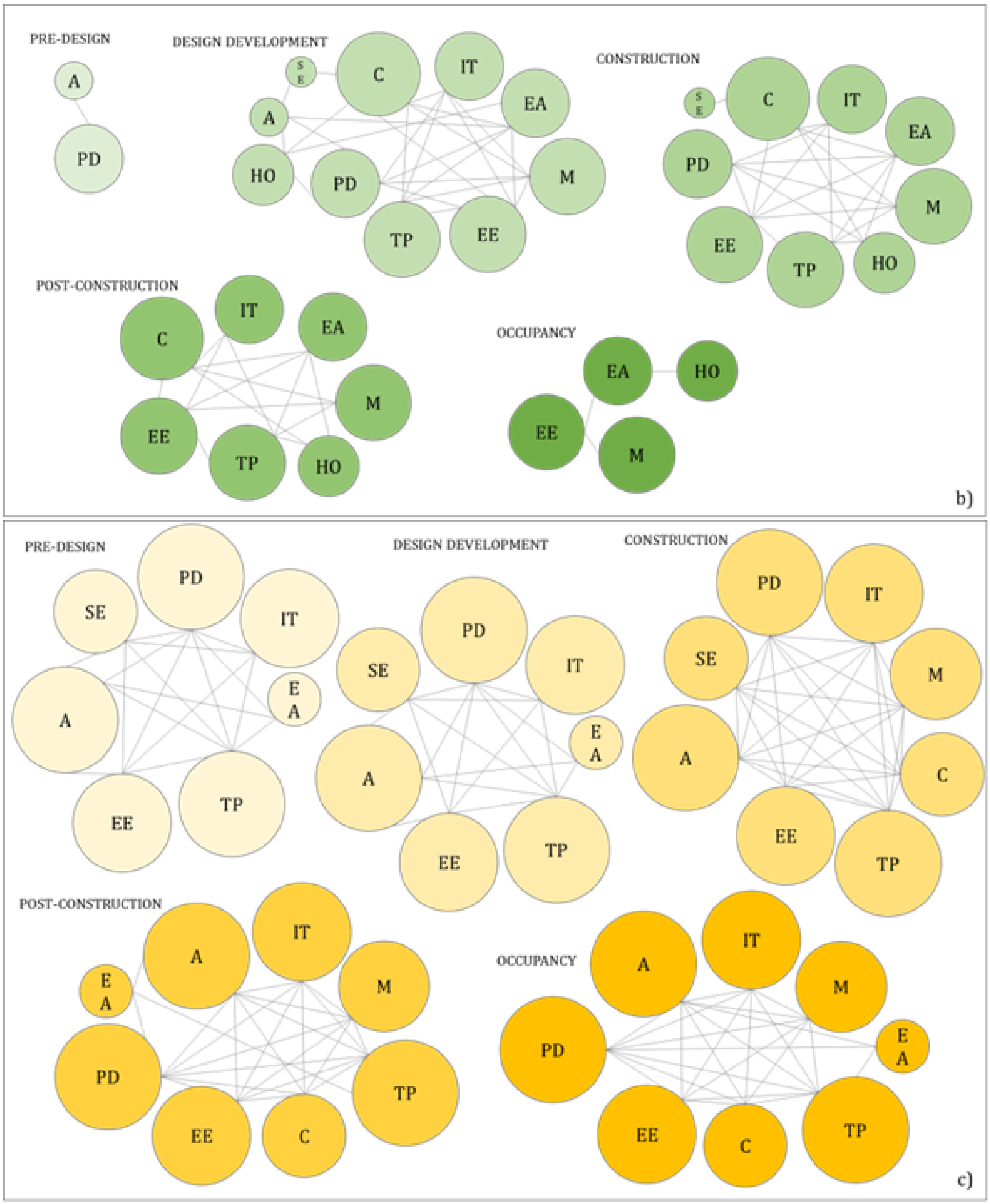


Figure 13: Stakeholder involvement and communication network in each project phase for a. UK, b. Italy, c. Cyprus. Key: A – Architect; **C –** Contractor; **EA –** Energy Analysis Expert; **EE –** Electrical Engineer**; IT –** IT Engineer; **M –** Monitoring Coordinator; **PD –** Project Developer; **SE –** Structural Engineer; **TP –** Technology Provider; **HO** – Home Owner/Occupant**.**

4.4 Drivers and Barriers to ZEN implementation

As found in literature (section 2.1), there are multiple drivers to opt for zero energy neighbourhoods as opposed to single ZEBs. The drivers resulting from the developed ZEN approach, as these have been recorded by the partners involved in the development and implementation of the approach through four pilot ZENs, are listed in Table 5 and have been further correlated with the stakeholders that can influence their achievement.

Table 5: The benefits of the ZEN approach and the stakeholders related to the realisation of benefits

Internal Stakeholders	External Stakeholders
Driver: Improved microclimate conditions through urban design solutions	
Design Team (Architects, Engineers) Consultants (Energy analysis expert) Technology providers	Planning authorities for approval of settlement plan
Driver: A clear roadmap for achieving compliance with European regulations for energy efficiency in buildings	
Project Manager Design Team (Architects, Engineers) Construction Team Consultants Technology providers	Planning authorities for approval of necessary documentation
Driver: Increased efficiency through communal energy generation and management technologies	
Project Manager Project Owner Design Team (Architects, Engineers) Construction Team (Contractor, Installers) Consultants (Energy, Monitoring, IT) Technology providers Home owners	National regulations and Policies on energy sharing Utility Companies
Driver: Access to the required expertise	
Project Manager Project Owner Design Team (Architects, Engineers) Construction Team (Contractor, Installers) Consultants (Energy, Monitoring, IT) Technology providers Home owners/Occupants	
Driver: Optimization of energy performance through optimized technology design and optimized integration of renewable energy and energy management measures in the settlement	
Project Manager Project Owner Design Team (Architects, Engineers) Construction Team (Contractor, Installers) Consultants (Energy, Monitoring, IT) Technology providers Home owners/Occupants	
Driver: Economies lead to lower initial investment costs for owners	

Internal Stakeholders Project Manager Project Owner Design Team (Architects, Engineers) Technology providers
Driver Energy savings and enhanced quality of life for the occupants
Internal Stakeholders Project Manager Design Team (Architects, Engineers) Construction Team (Contractor, Installers) Consultants (Energy, Monitoring, IT) Technology providers Home owners/Occupants

Together with the drivers, there is an equally long list of barriers that limit or challenge implementation and potentially hinder the realization of benefits (Table 6). The identified barriers can be divided into two main groups as follows:

i. Regulatory barriers, related to local and national planning processes and regulations, that may potentially discourage, limit, delay, or prevent the implementation of ZENs. These include, but are not limited to, barriers related to long-term urban planning, building permits approvals, and the approval of communal and hybrid renewable energy systems.

ii. Project management-related challenges that result from the novelty of the approach, which requires collaboration and the alignment of a diverse project team. These include barriers related to the alignment of the project team, the slow adaptability of the project team to cooperate in unexpected circumstances, the integration of existing and new technologies in local systems and supply chains, reaching agreement among different owners in the settlement, and cooperation with occupants.

Table 6: Project stakeholders and related barriers as encountered during the implementation of the 4 pilot ZEN.

Internal Stakeholders	External Stakeholders
Project Manager Project Owner Design Team (Architects, Engineers) Construction Team (Contractor, Installers) Consultants (Energy, Monitoring, IT) Technology providers Home owners/Occupants	Planning authorities Utility Companies
Internal Barriers	**External Barriers**
Assembly of an aligned team with good understanding and communication	Local long-term urban planning might obstruct design intentions

Experience Timely exchange information Integrating of novel technologies in local systems and supply chains Agreement among multiple owners Occupant cooperation	Reluctance to approve design when authorities are not familiar with the concept Existing policies and regulations on energy sharing schemes
Project phase	
ALL	Pre-design and Design

4.5 Discussion

A clear roadmap to integrated design, construction and monitoring has been developed and implemented in four pilot ZENs. The process involves design iterations, design optimization, holistic approach to design, an expanded team of diverse experts and continuous monitoring. Integration is a key concept in design and construction of a sustainable, high energy performance built environment and it has been thoroughly adopted.

As experience from implementation of the process has revealed, supported by the stakeholders' analysis, the technical knowledge and expertise exist to implement ZENs. However, integration of the expanded team of stakeholders that need to get involved in the process can be challenging. Considering the encountered barriers, the implementation of the ZEN approach is essentially challenged by two main issues: 1.the external barriers that are raised by the planning policies and regulations and 2.the challenge of internal stakeholders' management and integration.

Worldwide, regulations and standards have been adopted towards the wider implementation of zero energy buildings [16]. However, there seems to be a lack of coordinated policies and regulations for the implementation of communal solutions towards ZENs [37]. This has been a prominent barrier experienced in the implementation of the four pilot ZENs. Therefore, in view of transitioning from single buildings to communities, policy and regulations stakeholders need to be aligned with the design concepts and components (innovative technologies, shared energy schemes, communal energy management) that enable such transition.

To this end, the policy and regulation framework needs to incorporate provisions that expand from single buildings to communities, by introducing guidelines, protocols, and by-laws which will facilitate, and supervise the implementation of such concepts and aims. This expansion will motivate stakeholders such as energy companies in developing renewable energy sharing programs in support of zero energy and smart communities [173].

As the stakeholder analysis revealed, the ZEN implementation presupposes an expanded team and close collaboration among the partners throughout the process. This type of collaboration is inherent to the IDP and is expected for creating ZENs. Coordination and integration of the internal stakeholders and their interactions need to be ensured, and would preferably be handled by a Project Manager who has a broad overview of the project. Findings from literature on sustainable design and the IDP confirm these results [83], [81], [12]. In [83] this role is assigned to the architect. A Design Facilitator who guides the process is proposed to undertake this managerial role that can be challenging for architects [12], [81].

Since integration is a key requirement, traditional project management structures are not applicable. The traditional approach to design and construction is characterized by fragmentation that hinders the project's quality management. However the transition is not an easy process and building design and construction practitioners throughout the world have been challenged by it. Stakeholders' willingness to embrace change and adopt new processes has been identified as common barrier to adapting to change, [91,174,175]. Resistance to change has also been identified as the main barrier to the adoption of green technologies in the US [175]. Building design and construction stakeholders feel more comfortable implementing processes and tools they are familiar with [174–176].

Main challenges faced by project managers in green construction projects, according to review conducted in [176], are technical difficulties due to complexity of design, extra attention to the contract forms used, that need to be integrated, long time for approval of green technologies, lack of experience of project managers on working with green technologies and maintaining good communication through multiple communication channels with stakeholders. The list of barriers recorded by the project partners from the pilot ZEN is similar.

The most critical project management challenge in green construction projects, according to research participants from Singapore, is the long time required to complete the design process so as to achieve optimum integration of design parameters with involvement of multiple stakeholders. This is followed by the challenge of assembling the project team. On the contrary, the lengthy approval period of the technologies was not considered critical to project management [176]. Malin's statement that *"the very strength of integrated design is also its greatest weakness—it depends on collaboration from all the key players"* is thereby confirmed [80].

Policies and regulations can endorse the implementation of integrate design [80], [83] and drive change in project management and stakeholders' engagement [177,178]. Opportunities to endorse the implementation of the IDP appear in design competitions [94]. Besides, communication campaigns need to support prospective policies and regulations. Lack of effective communication and enforcement will risk adequate understanding and implementation [178].

In the new form of collaboration, the owner is a key stakeholder throughout the project [12,83]. This is confirmed by experience from the pilot ZENs, where the Project Owner/Developer had a high level of involvement and communication links. However, the Project Owner is not necessarily the final home-owner and occupant. In the UK pilot, the Project Owner is the developer of a neighbourhood and the eventual manager of the neighbourhood. In this case, the home-owners and occupants buy the residences with the monitoring equipment and settlement energy generation technologies already installed. In other cases, such as in the Italian case study, the project developer has included the buyers and eventual home-owners and occupants of the residences in the process. Consequently, there is different involvement of the final owners or occupants (and possibly non-involvement), depending on how the project developer operates. In the latter case, the home owners have influenced with their decisions and requirements the course of the project development.

Committed clients as well as engaged clients and occupants are critical for the success of the design process and the in-use performance. In turn, design decisions are led by the client requirements and occupant satisfaction [76,179]. Occupant engagement is also a driver for mindful building operation that is critical for mitigating the performance gap commonly associated with the zero energy, high performing designs [52,72,180]. The home owners' level of cooperation, e.g. acceptance of sensors or innovative technologies, may be affected by perceived rather than actual systems complexity, by technophobia, misunderstanding and misconception, lack of interest in the new technologies and the potential they provide, or simple laziness [181], [153].

Occupants' cooperation involves their willingness to allow and facilitate periodic surveys and share personal information and data with researchers as part of POE [179]. The necessity of this can be clearly delineated in a Welcome Package. For the pilots Welcome Packages have been prepared and distributed to the occupants. These are non-technical user guides that contain basic information about the technologies and the monitoring equipment, guidance on accessing the monitoring platform, and contact details of technical support. The scope of the POE is also explained. Nevertheless, there is the risk of occupants' losing interest and getting tired of the POE surveys, which could reflect on the POE results and the much needed user-feedback for performance evaluation after occupancy.

The technology providers have also emerged as prominent members of the stakeholder team for the creation of ZENs. The achievement of the zero energy targets requires the use of technologies for energy conservation, energy management, and energy generation. Similarly, at the neighbourhood level technologies need to be integrated to achieve the targets. Therefore, both at the building and the neighbourhood level, technology providers need to be part of the team and communication network early on for optimum technology integration and integrated design performance evaluation. The technology providers match the stakeholder category that is identified in the Guide to Integrated Design and Delivery as "manufacturers" and "*includes those who might participate in an integrated project in the capacity of a product development specialist or product representative*" [83].

After installation and commissioning, continuous monitoring of the technologies is part of the settlement-level monitoring. Continuous monitoring is essential for performance evaluation and energy management. As a result, the roles of the Monitoring Expert and IT Engineer are part of the stakeholders' team for the ZEN. The Monitoring Expert leads the overall planning and implementation of the monitoring, including measurement and sensor specifications, design of the monitoring schema, monitoring equipment placement, and quality control procedures. Consequently, the Monitoring Expert needs to be involved in most phases and form multiple communication links. The IT Engineer (or Data Engineer) is the developer of the platform where the monitored data are being recorded and also forms a series of interactions to ensure the correct function of the monitoring schema and the data logging platform.

Participation of these roles in the stakeholders' team and the related interactions are imperative for high performance zero energy buildings and neighbourhoods since monitoring has become an integral part of design and operation. However in existing guides these roles have not been identified in the context that is discussed here. In [81] the role of Controls Specialist is identified for proposing control strategies and ensuring that these work. Specialty consultants are provisioned in [83] that might be included in the project according to the project scope and possibly have a prominent role depending on the significance of their activities within the project.

5 Integrated Measurement and Verification

This part specifically focuses on the Measurement and Verification component of the process. The newly developed M&V framework that was followed for the M&V of the four zero energy neighbourhoods is described.

Although the M&V protocol for single net-zero energy buildings is available [98], a neighbourhood is an entity more complicated than a single building. A neighbourhood is composed of more than one buildings of similar or various uses, where energy is communally produced, stored, and managed. When considering a neighbourhood a new boundary is introduced where, apart from the building entities and building-level technologies, settlement level technologies and settlement microclimate are also included in the assessment. Nevertheless, the aim is not to provide a new protocol but rather a novel framework for incorporating and implementing the guidance provided in established protocols.

Gupta et al. have identified that building performance evaluation is a fragmented field with multiple techniques and methods available. As a response to this fragmentation, they propose a structured and flexible building performance evaluation framework, mapping the various tools to the building life stages. The framework is applicable to both existing and new buildings spanning from a basic to an advanced performance evaluation level, where increasing level is linked to increasing cost [106].

Apart from the aforementioned work, existing literature lacks a more comprehensive methodology for measuring and verifying the performance in the various phases of a new-built project, especially when shifting the scale from the single building to the neighbourhood level. Therefore, the present section specifically discusses how the M&V can be placed within the project management and as part of a project's design, construction and operation. This is a novel structured, integrated proposal for designing and implementing M&V for zero energy buildings as part of zero energy neighbourhoods.

5.1.1 M&V Framework development

Planning the M&V of a project is a complex process that involves the coordination of various actions. M&V protocols exist—IPMVP [86], ASHRAE Guideline 14 [87], Measurement and Verification Protocol for Net Zero Energy Buildings [98]—that outline the actions and contents of an M&V Plan. These may be supplemented by project-specific instructions that are given in international standards, e.g., EN 16798-1:2019 for indoor environmental quality assessment [182], EN ISO 52000-1:2017 for the definition of the energy performance of buildings [183], ISO 50001:2018 for monitoring the energy management at settlement level [184].

The methodology followed for the development of the proposed M&V framework is depicted in Figure 14.

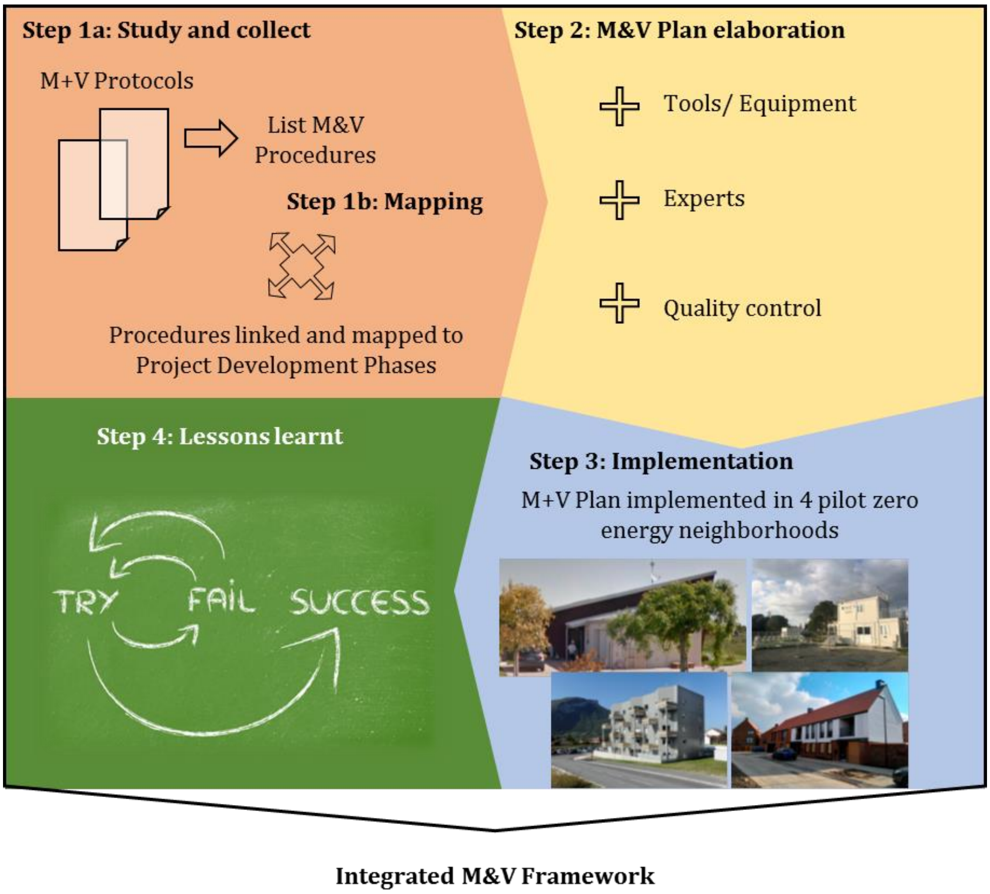


Figure 14: Schematic representation of the measurement and verification (M&V) methodology.

In the first step, the existing M&V protocols and standards are studied and their procedures are linked and mapped to the project development phases. In the next step, the M&V Plan is elaborated to include the tools and equipment that are needed for performing the various M&V procedures, the experts that are involved in each phase as well as quality control provisions for each stage. The developed M&V Plan is implemented in 4 pilots, and finally, the lessons learned from its implementation are obtained. These steps resulted in an integrated M&V Framework that is incorporated into the whole Project Management workflow.

For optimum planning of the M&V activities for the pilot settlements, it was decided to organize the M&V in phases matching the project development phases. These were broken down as follows for the four pilot settlements:

- Design Phase
  - Pre-design
  - Design development
- Construction Phase
  - Construction
  - Post-construction/Pre-occupancy
- Occupancy

To further support the M&V planning, the measurement and verification procedures were grouped into the following categories:

- Building diagnostics tests
- Physical testing of the technologies
- Building monitoring
- Social science surveys: Post Occupancy Evaluation (POE)

Table 7: Mapping of M&V procedures concerning the project development phases for the four pilot settlements.

<table>
<tr><th></th><th>Building diagnostics</th><th>Physical Testing of Technologies</th><th>Building Monitoring</th><th>Social science surveys</th></tr>
<tr><td>Pre-Design</td><td colspan="4">Selection of expert partners
Goal setting</td></tr>
<tr><td>Design development</td><td rowspan="2"></td><td colspan="2">Energy boundaries
Data to be monitored
Monitoring technology
Quality control</td><td rowspan="3"></td></tr>
<tr><td>Construction</td><td colspan="2">Proper installation and function
Commissioning</td></tr>
<tr><td>Post-construction — Pre-occupancy</td><td>Commissioning procedures</td><td colspan="2">Pre-occupancy monitoring
Commissioning</td></tr>
<tr><td rowspan="2">Occupancy</td><td>Tests performed during the 4th phase may be repeated</td><td colspan="2">Post-occupancy monitoring
Data post-processing and analysis
Quality control</td><td>Questionnaires</td></tr>
<tr><td colspan="4">Reporting</td></tr>
</table>

Finally, a mapping of the procedures and the project development phases was produced (Table 7). This mapping forms the basis for further development of the M&V. This method of organizing the M&V is intended to provide confidence in the process ensuring that, in every step, the necessary actions are taken towards obtaining credible measurement and verification results.

5.1.2 M&V Framework

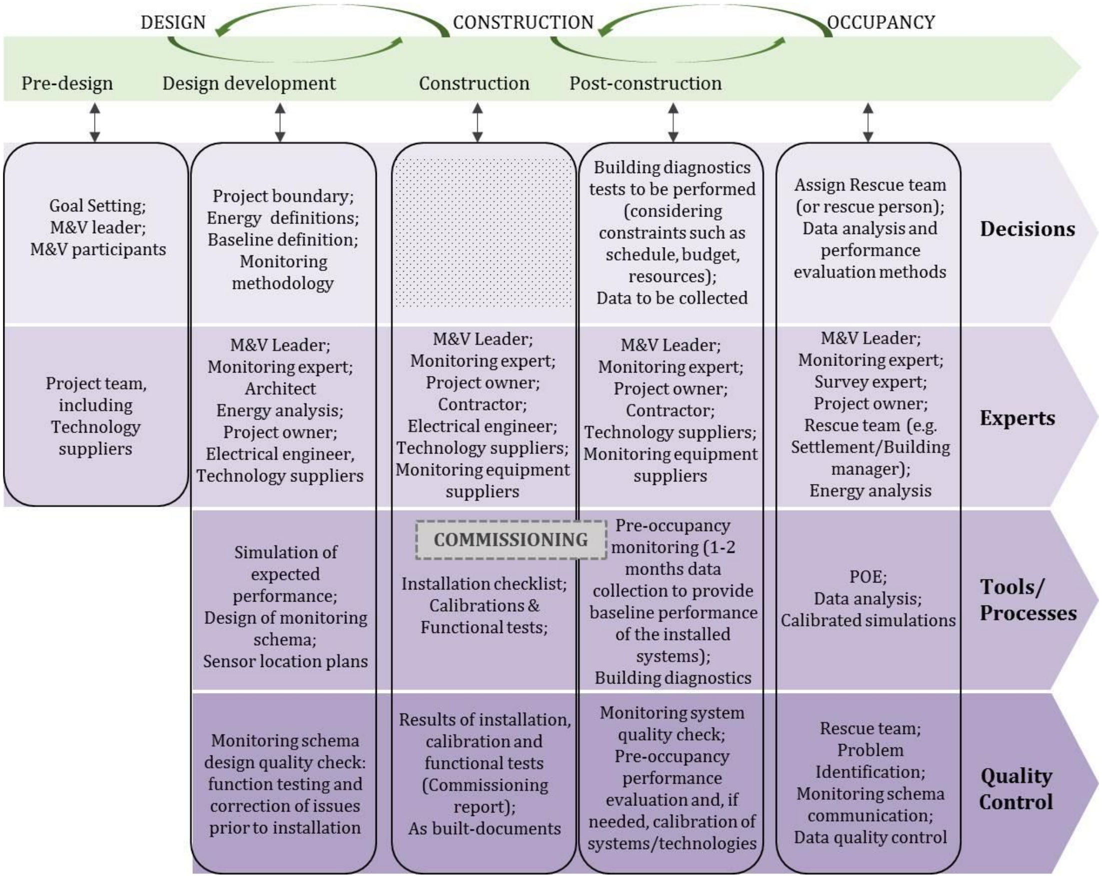


Figure 15: Graphic representation of the M&V framework that has been developed and implemented in the four pilot neighbourhoods.

Figure 15 is a graphic representation of the M&V framework as it was designed and implemented in the four pilot neighbourhoods. It depicts an integrated framework where the M&V development is placed and implemented within the project management process and includes the decisions to be made in various phases, the experts to be involved, the tools to be used, and the processes to be implemented as well as quality control actions.

5.1.2.1 Pre-Design

The pre-design is the phase that establishes the targets of the project. The performance targets that are subject to measurement and verification in a neighbourhood project can be defined for the whole neighbourhood as well as for individual buildings or building types within the neighbourhood, or systems of the neighbourhood. Setting a clear vision of the M&V targets and expectations assists in identifying the measuring approach to be followed and, as a result, obtain a view of the expected effort in human resources and costs. M&V responsibilities are distributed among the project team members with relevant expertise. A partner, preferably with expertise in monitoring, is selected to lead the process (M&V leader), supported by partners with individual expertise on the various M&V components (i.e., monitoring expert (if not the M&V leader), energy analysis expert, survey expert).

5.1.2.2 Design development

The design development phase includes all the definitions, analyses, decisions, and planning that should be defined before the neighbourhood's construction. These include the zero energy neighbourhood boundary, the baseline of performance, the expected energy performance, energy definitions, and monitored data.

The existing M&V protocols address the evaluation of implemented energy-saving measures, offering different boundary options, from a single system to a whole building boundary [86,87]. Specifically, the ZEB balance evaluation is determined by the selected energy boundary [98]. The measurement and verification of a ZEN becomes a more complex task. The energy balance boundary might include energy flows within a micro-grid, in which case automated M&V becomes imperative for monitoring and regulating energy towards the improvement of the zero energy performance.

Furthermore, the design intentions are subject to evaluation. For a neighbourhood, this includes microclimate conditions, settlement energy production, building energy consumption, and IEQ conditions. These targets' achievement can be assessed following the calibrated simulations option outlined in the existing protocols [86,87]. Informed planning is still crucial for selecting the metrics to be measured and the measuring approach (including equipment) to provide the necessary calibration data.

Therefore, at this phase, the monitoring methodology is designed, including data to be measured, measuring specifications, the monitoring equipment to be installed, the connections and communication of the monitoring schema, as well as the placement of the monitoring equipment (e.g., sensors within houses, or a weather station in settlement).

Sensor location plans are produced in coordination with architectural and electrical plans. During the design development phase, the building sensors' placement needs to be considered along with interior and electrical design. Besides, the location of a weather station in the settlement needs to be decided at this stage. Therefore, at the end of this phase, a set of plans indicating the equipment's location will be prepared. Furthermore, the electrical drawings need to include the monitoring installation. The decisions and designs of this phase are updated and re-evaluated along with the overall design development. This design phase planning assists the construction and installation phases, and it has been highlighted through the lessons learned as a practice to be adopted in future projects.

Quality control procedures for testing the proper function of the designed monitoring schema and its communication with the data collection platform are prepared and implemented at this phase prior to installation on the neighbourhoods. Possible deficiencies that might be identified are resolved before installation of the monitoring equipment. The budget for the purchase of monitoring equipment can also be approximated after deciding the list of measurements.

5.1.2.3 Construction

This phase comprises the measurement and verification procedures to be followed during the construction of the neighbourhoods and installation of the technologies and monitoring equipment. These procedures are intended to ensure the proper installation and function of the technologies and monitoring equipment. Most of the processes fall into the field of quality control and are closely related to commissioning.

A commissioning plan is devised and implemented to ensure proper installation of the building systems and technologies. It includes a check list for installation as well as functional testing. Any changes made during construction/installation are recorded and as-built documents are prepared.

At this stage the monitoring equipment supplier has the responsibility of installation, calibration, and testing proper function of the equipment. If such service is not available from the supplier, project owners/contractors need to employ staff with expertise in performing installation, calibration, and functional testing of the monitoring equipment.

5.1.2.4 Post-Construction—Pre-Occupancy

Post-construction—pre-occupancy measurement and verification procedures include commissioning after constructing the neighbourhoods and installing the technologies and monitoring equipment. These procedures are intended to monitor both the systems' simultaneous and individual performance and evaluate them against the project's targets. Essentially, this phase is the first monitoring and evaluation of the neighbourhoods' performance prior to occupants moving in. It is proposed to acquire data for approximately 1–2 months pre-occupancy to provide a baseline of performance for the installed systems' calibration purposes.

Similarly to the previous phase, this phase's tests coincide with tests that are expected to be included in a project's commissioning plan. Because systems testing and monitoring equipment's testing are linked, the technology providers, monitoring equipment providers, monitoring expert, contractors, and project managers are involved.

5.1.2.4.1 Building Fabric

Building diagnostics tests are intended to evaluate the physical performance of the building fabric. Project managers can decide which tests they would like to carry out, considering constraints such as the schedule, costs, experts' availability, etc. In the pilots, it was decided to perform a minimum evaluation test for the building fabric's U-value and airtightness.

5.1.2.4.2 Systems Testing

Systems' testing is essential for measuring the technologies' performance, energy use, and environmental parameters, and is linked to the monitoring system that gathers the data. Consequently, during this phase, the function of the monitoring system is tested as well.

5.1.2.4.3 Monitoring System Testing

At this phase, the monitoring system has been installed comprising multiple sensors and monitoring devices that communicate with a data collection platform.

A series of tests is decided and implemented by the monitoring expert. The purpose of the tests is to collect data during a test period and cross-check them with the data provided by the internal data logging of each device to verify the system's performance and accuracy. The monitoring expert monitors and corrects any faults in the monitoring schema and data logging. These procedures are intended to complement and not replace any instructions provided by the monitoring equipment's suppliers. The monitoring equipment suppliers need to be available during this phase to fix the sensors' possible faults if required.

5.1.2.5 Occupancy

During Occupancy, the neighbourhood's performance monitoring, including single building and technology performance monitoring, is in progress.

Data post-processing and analysis is executed at this phase. The method to be applied for verification of performance is decided depending on the project's evaluation objectives. Apart from the options provided in the M&V protocols, the measured performance is assessed and verified versus the project's performance targets. Social science surveys (i.e., interviews, questionnaires) are implemented as part of the POE measurement and verification procedures.

Furthermore, quality control procedures are planned for defining monitoring responsibilities during occupancy, evaluation of measurements and results, and troubleshooting (e.g., lost data).

5.1.2.5.1 Quality Control

Continuous monitoring responsibilities are assigned to a rescue team (or person) that undertakes the task to address problems that might occur, such as sensors' faults, technologies' faults, monitoring schema communication failures, etc. The rescue team can also provide clarifications and support to the occupants. This role can be undertaken by the neighbourhood manager or the neighbourhood's maintenance service.

During occupancy, continuous fault detection of the monitoring equipment is implemented. Periodic calibration of sensors is proposed to be implemented during continuous monitoring, as indicated by the manufacturer, to check accuracy. Data loss might be experienced due to sensor failure, power disruption, or errors in data transfer. In case of any failure, the rescue team is notified of faults, verifies the faults, and takes corrective actions (in collaboration with the M&V leader or monitoring expert, if needed). Subsequently, appropriate procedures for cleaning and imputing missing data are set in place. Quality control during occupancy ensures the collection of a high-quality dataset, thus building trust in the obtained results.

In the monitoring schema that has been designed for the pilot ZENs, the implemented steps during continuous monitoring as part of the data quality control are:

1. Assessment of measurement errors [185] before the measurements are added to the platform.
2. Detection of lost data: this is based on the expected amount of collected measurements within a timeframe, considering the measuring resolution.
3. Implementation of data imputation procedures based on the amount and pattern of missing data.

Post-occupancy quality control has provided invaluable feedback regarding cases of lost communication and missing data (Table 8).

Table 8: Quality assessment of the collected data, quality indicator: completeness

	Italy	UK	France	Cyprus
Reasons for missing data	Equipment updates Electric power disruption COVID-19	Equipment updates Electric power disruption	Equipment malfunction	Internet connection issues
% of missing data	20%	3%	15%	1%

In the pilot ZENs, missing data occurrences have been recorded due to system communication disruptions and sensor malfunction. Sensor malfunction is related to the faulty reading of the measurements. Communication disruption has been attributed to internet connection problems, electric power disruption, or individual component updates. Having a quality control mechanism allows the timely identification of the problem source and immediate appropriate mitigation actions. The COVID-19 lockdown has caused a period of lost data spanning from mid-February to mid-July 2020 in one of the pilots where technical assistance could not attend to the problem. Indeed, not all issues can be resolved remotely. Keeping a record of missing data occurrences and implementing suitable data imputation procedures has been identified by the partners as useful good practice.

5.2 Discussion

In this section a comprehensive M&V framework for neighbourhoods has been presented, structured in steps, including tools, processes, and involved experts for each step, highlighting M&V quality aspects and identifying links with the M&V 2.0. This framework can be especially useful to project managers for integrating M&V into the integrated project management and development process and specifically aligning it with the rest of the design and construction procedures.

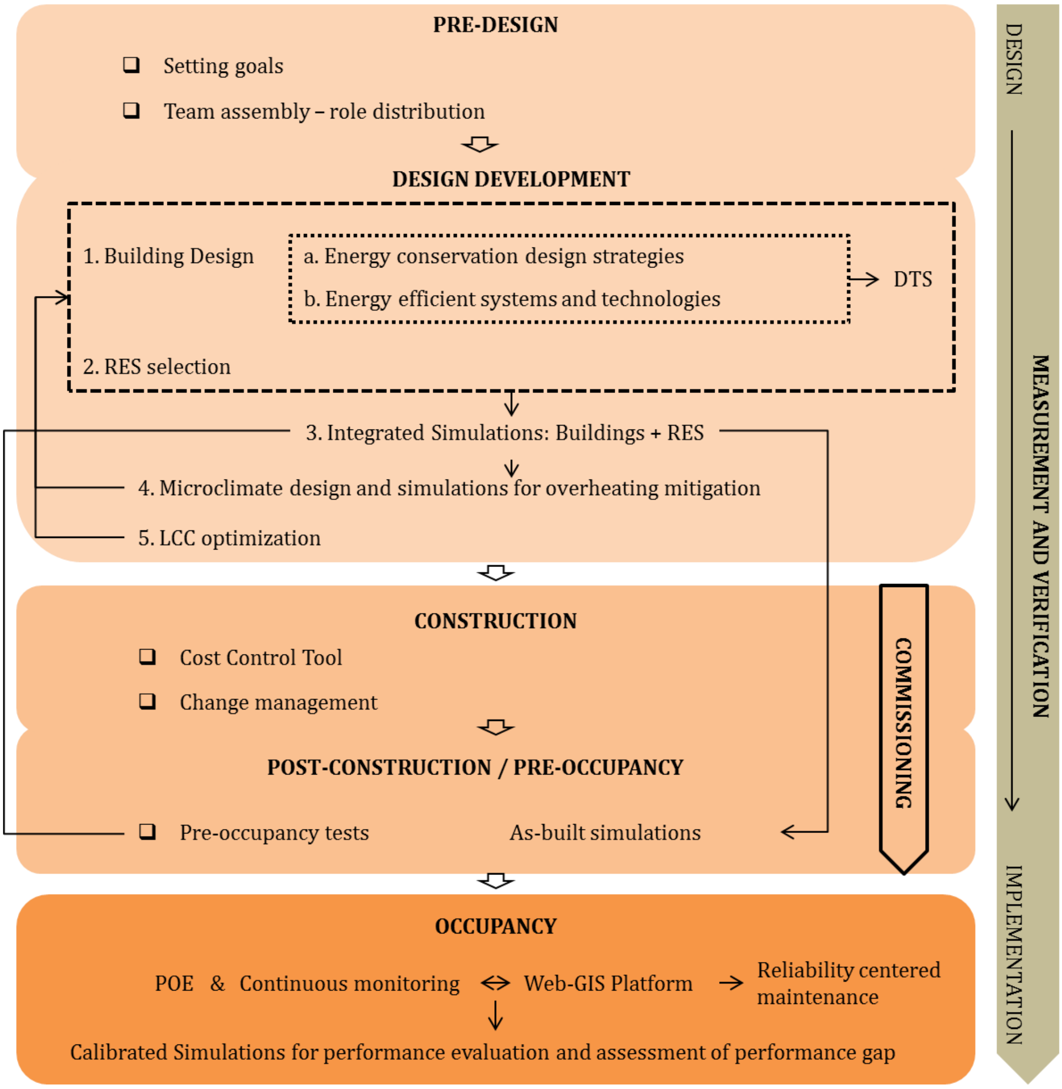


Figure 16: The M&V planning and implementation is integral to the IDP, linked to the IDP development and implementation.

An integrated M&V framework to assess the field performance of ZENs has been developed and implemented. The M&V activities have been recorded in an M&V Plan, continuously evolving along with the project development and updated as needed. In that sense, the M&V has been developed with an integrated design approach. Planning the measurement and verification of a new-built project is a complex process integral to IDP, and the approach that has been followed demonstrates how the M&V design and implementation are related to each of the IDP steps, although intended to serve as the last step of the process (Figure 16).

Therefore, for new-built projects in the era of zero energy buildings and communities, where the IDP has emerged as the proposed approach for achieving the seamless design, construction, and operation of buildings, the M&V needs to be viewed as part of the project management and development process. This has been also confirmed by the approach of Gupta et al. [106].

Especially planning of the M&V activities for the construction and post-construction phase demonstrates that Commissioning and the M&V are linked. Commissioning is closely related to measurement and verification because it ensures that the technologies and the monitoring schema are functional. Hence, it provides a trusted basis for assessing initial performance after installation that allows the elimination of "procurement" as a possible reason for poor performance when investigating a possible performance gap.

Quality control in particular is a significant task within the M&V. In light of the M&V 2.0, the M&V planning and quality control procedures are highly relevant. M&V 2.0 proposes a fully automated M&V system that can be both cost-saving and time-saving by offering immediate performance assessment and energy-savings feedback [121,186]. Quality control in every phase has to ensure the interoperability and smooth communication of the various components. The ultimate goal is reliable, high-quality data collection that is the basis for performance assessment and verification. This is imperative when measuring and verifying a neighbourhoods' performance with multiple data sources.

6 ZERO ENERGY NEIGHBOURHOOD CASE STUDY ANALYSIS

6.1 Introduction

In the zero energy communities' state of the art, research discussing simulation results is more widespread than research on measured performance results. Realized examples and measured performance results are necessary for the proof and evolution of the concept. Therefore, the basis for this section is a real case study that has been designed and constructed to be a zero energy neighbourhood (ZEN) following the integrated approach that was presented in the previous section.

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 [16,23,24,38]. Consequently, this ambiguity is transferred to the neighbourhood scale [39]. At neighbourhood scale, extra considerations can be entered, such as the inclusion of all types of energy in the balance [44], as well as neighbourhood characteristics that contribute to or hinder the balance [6].

The case study studied herein is composed of high-energy performance residential buildings and on site RES. Therefore, the case study is a "site renewable energy" neighbourhood that its RES production aims to balance its energy needs. The ZEN has the performance targets set by the ZERO-PLUS project.

The present section focuses on the analysis and evaluation of the first year of monitored performance data obtained from the pilot ZEN, representing the period June 2019 – May 2020. The aim is to evaluate the performance of the neighbourhood on three aspects: a. identification of a possible performance gap (section 6.3.1), b. validation of the design performance targets (section 6.3.2) and c. assessment of the zero energy balance (section 6.3.3).

6.2 Neighbourhood overview

The pilot neighbourhood is part of a housing development area currently under construction in Granarolo dell'Emilia, in Emilia-Romagna, Italy. 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 (Figure 17). 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 liveability of the entire area.

Figure 17: The residences in the pilot ZEN (top) and the development under construction in the background (bottom).

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 9.

Table 9: 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^{2}K	0.164 W/m^{2}K
Roof U-value	0.117 W/m^{2}K	0.117 W/m^{2}K
Floor U-value	0.167 W/m^{2}K	0.167 W/m^{2}K
Window Ug	0.600 W/m^{2}K	0.600 W/m^{2}K
Glazing	Low-e triple glazing with argon-filled cavities	
Window shading	Manual blinds	

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. Figure 18 shows the schematic of the HVAC system inside the buildings.

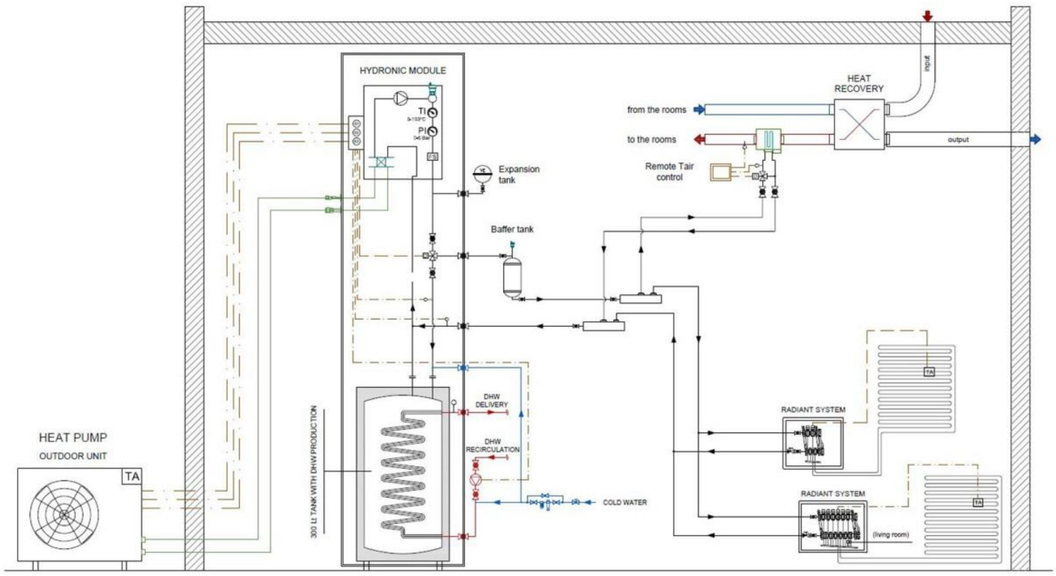


Figure 18: schematic of the HVAC system inside the buildings.

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 [187];
- XPS insulation for energy conservation;
- PV polycrystalline panels 12 kWp for renewable energy production;
- Energy storage system (Li-Ion battery with 2 kWh capacity) and control platform;
- Load Control system for load management;
- Home Energy Management System, for building energy management.

The PV panels are located on the rooftops of the residences (Figure 19). The energy produced by the PVs is used in the following order:

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

At the time of construction and first year monitoring, the concept of shared energy communities had not yet been enacted by Italian regulations. Therefore, each building could consume only the PV production by the panels located on its rooftop. For the present analysis, it is assumed that PV production sharing is possible. The PV production target is calculated as follows:

$$Total\ PV\ production\ in\ the\ year\ /\ Sum\ of\ residences\ net\ floor\ area \geq\ 50kWh/m^2/year$$

Figure 19: PV panels on the rooftops of the residences.

6.2.1 Neighbourhood monitoring

For effective monitoring of the ZEN performance, the integrated measurement and verification framework, that that was presented in section 5, has been implemented.

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 neighbourhood's monitoring scheme, where all the information from the various sources (sensors inside rooms, energy monitoring of RES, weather station etc.) is gathered, stored, analysed and presented to the users [171].

All collected data are transmitted in near real-time to the Web-GIS platform and the sampling time is 15 minutes. A full list of the measured quantities, measurement units, measuring devices and their location is given in Table 10. The measurement specifications (range, resolution, and accuracy) as well as the monitoring timeline are listed in Annex I.

Table 10: List of measurements, measurement units, measuring devices and their location

Measurement name	Units	Device	Location
Space temperature	°C	temperature, relative humidity and CO2 sensor	Living room of each residence
Space relative humidity	%		
Space CO2 level	ppm		
Space occupancy	0/1	presence and illuminance sensor	
Space Illuminance	Lux		
Window open/close	On/Off	open/close status sensor for windows and doors	
Door open/close			
HVAC set point	°C	thermostat	
Building appliances electric power	W	power/energy meter for electric appliances	Electric rack of common services
Building appliances electric energy	Wh		
Building HVAC electric power	W	power/energy meter for HVAC	
Building HVAC electric energy	Wh		
Building DHW	Wh	energy meter for DHW	
Building PV power	W	PV production meter	Integrated on the PV inverter
Building PV energy	Wh		
Building battery electric energy stored	Wh	electric Energy charge/discharge meter	
Outdoor air temperature	°C	meteorological station	On the roof of Residence 2
Relative humidity	%		
Wind Speed	m/s		
Wind direction	deg		
Rain	mm		
Global radiation	W/m2		

Figure 20 is a graphical representation of the neighborhood's data collection schema. The monitoring devices for IEQ (Figure 21) and building energy consumption (Figure 22) 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 [188]. 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.

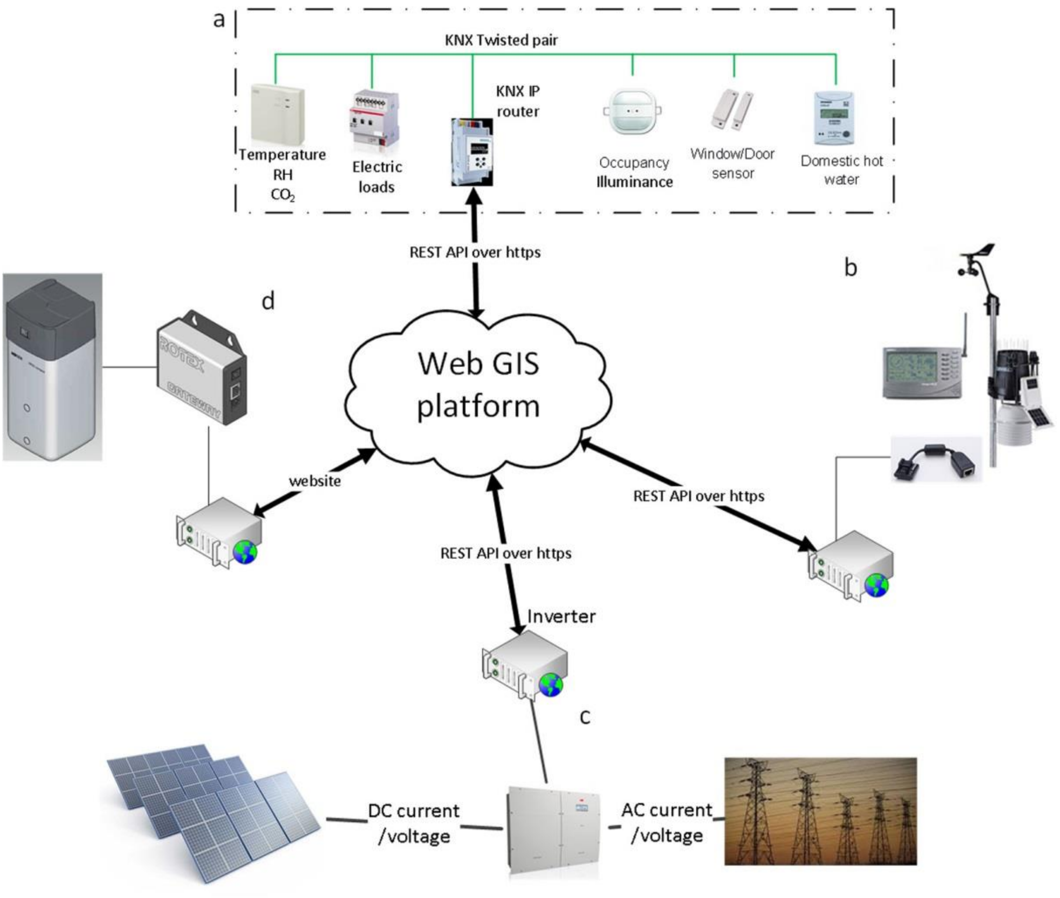


Figure 20: The data collection schema: a) The IEQ and building energy consumption monitoring devices, b) The weather station, c) PV, energy storage and national grid electricity monitoring, d) HVAC set-point monitoring. The Web-GIS platform is in the centre.

Figure 21: a) Presence sensor, b) Air quality sensor, c) HVAC thermostat.

Figure 22: a) Electricity metering, b) Heat pump energy meter, c) DHW meter.

The steps (Figure 23) towards quality data collection through the monitoring schema, contributing to quality M&V include:

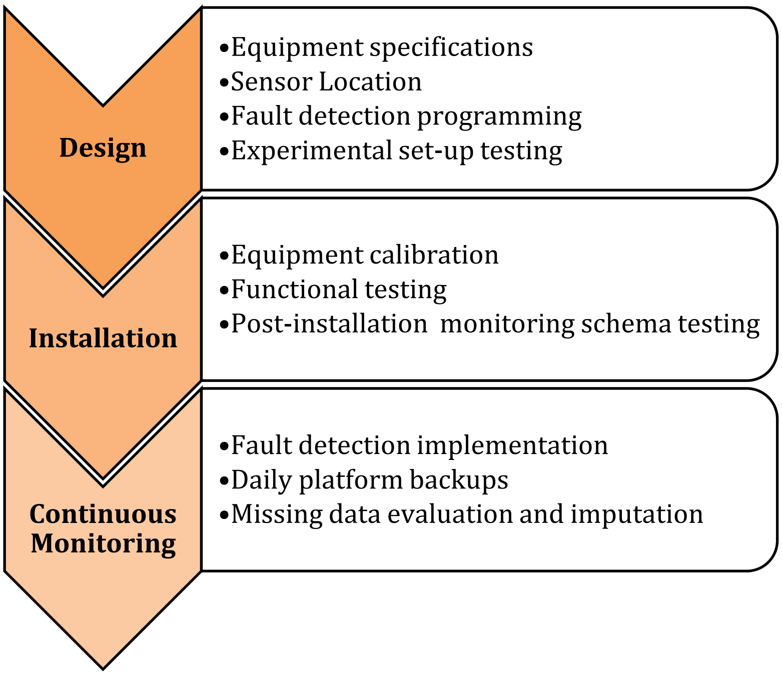


Figure 23: Steps towards quality data collection through the monitoring schema.

Data quality criteria can vary depending on the type of data collected and the purpose of data collection [189–192]. 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 [189]. In fact, accuracy and completeness have been identified as the main reasons for compromised data quality [193]. 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 accuracy and timeliness have been ensured as part of the monitoring schema design. The first by setting accuracy specifications for the measurements (Annex I) and the latter by using the Network Time Protocol (NTP) [194] that synchronizes the internal clock of all monitoring devices. In Annex II are given the details of uniqueness and completeness of the collected data for the period 9/6/2019-8/6/2020.

6.2.2 Simulated performance

The expected performance – heating, cooling, mechanical ventilation, domestic hot water (DHW), equipment, lighting consumption and PV production – of the pilot neighborhood was simulated with the EnergyPlus dynamic simulation engine [195]. The graphical interface of DesignBuilder has been used for modeling. A single model was developed including the two buildings and the energy production systems of the neighborhood, namely building integrated and shared PVs. The buildings were 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 [196].

After completion of construction and commissioning, on-site pre-occupancy checks and pre-occupancy monitoring have been performed prior to residents entering the buildings [172]. 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 was 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 11.

Table 11: As-built simulated performance of the pilot ZEN

		Residence 1	Residence 2
kWh/m²/y	**Design targets**	**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

A second calibration has been performed after one complete year of monitoring to reflect actual conditions of operation, i.e. including systems performance and occupant behaviour. Occupancy and occupant-building interaction, different for the two buildings, have been modelled according to the insights from the POE and monitoring [172]. The details of the two stages of calibrations are given in Table 12.

Table 12: 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 Air-permeability from blower door test As-built design modifications (mainly in terms of windows and shutters)		HVAC Set-points and set-backs Occupants presence schedules Occupants building systems operation schedules	
Target parameter	Indoor air temperature		Energy consumption	
Calibration period	R1: June 19th - July 6th 2018 R2: February 1st - march 5th 2019		June 2019 - March 2020	
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%

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 Equation 1 for MBE and Equation 2 for RMSE.

$$\textbf{Equation 1: } \boldsymbol{MBE} = \frac{\sum_{i=1}^{n}(M_i - S_i)}{n} \quad [°C]$$

$$\textbf{Equation 2: } \boldsymbol{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(M_i - S_i)^2}{n}} \quad [°C]$$

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

According to the validation criteria specified in the ASHRAE Guideline14 [87], 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 Equation 3 and Equation 4 respectively.

$$\textbf{Equation 3: } \boldsymbol{NMBE} = \frac{\sum_{i=1}^{n}(M_i - S_i)}{(n-1)\,\bar{M}} \times 100 \quad [\%]$$

$$\textbf{Equation 4: } \boldsymbol{CV(RMSE)} = \frac{1}{\bar{M}}\sqrt{\frac{\sum_{i=1}^{n}(M_i - S_i)^2}{(n-1)}} \times 100 \quad [\%]$$

According to the validation criteria specified in the ASHRAE Guideline14 [87] the simulation model can be considered calibrated with NMBE < 5% and CV(RMSE) < 15%, considering monthly energy consumption values.

6.3 Measured performance results

6.3.1 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.

The monitored HVAC performance against the expected HVAC performance per month is presented in Figure 24 and Figure 25, 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 13. 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 to the COVID19 lockdown and continuous presence of occupants in the houses.

Table 13: 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

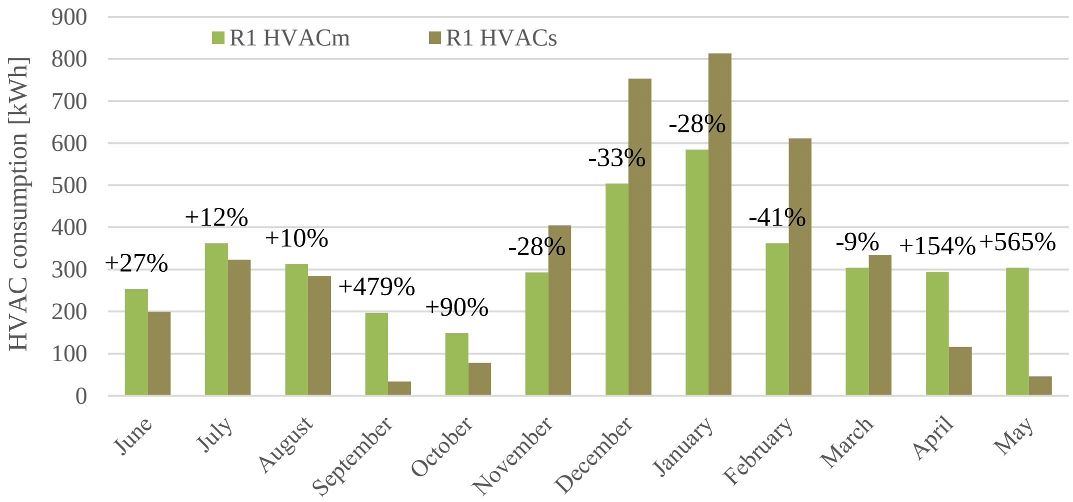


Figure 24: Monitored (R1HVACm) and simulated (R1HVACs) HVAC consumption of Residence 1, per month for the period of June 2019 – May 2020.

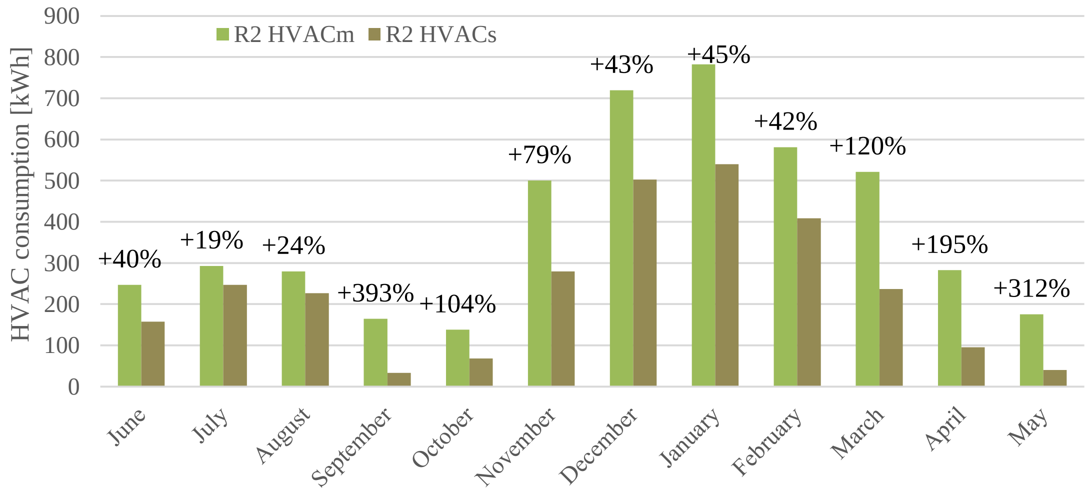


Figure 25: Monitored (R2HVACm) and simulated (R2HVACs) HVAC consumption of Residence 2, per month for the period of June 2019 – May 2020.

The energy signatures in Figure 26 and Figure 27 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 (Figure 26 and Figure 27). However, in R2, the monitored HVAC consumption (R2HVACm) is higher than the simulated one (R2HVACs), which is indicated by the shift of the signature (Figure 27).

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.

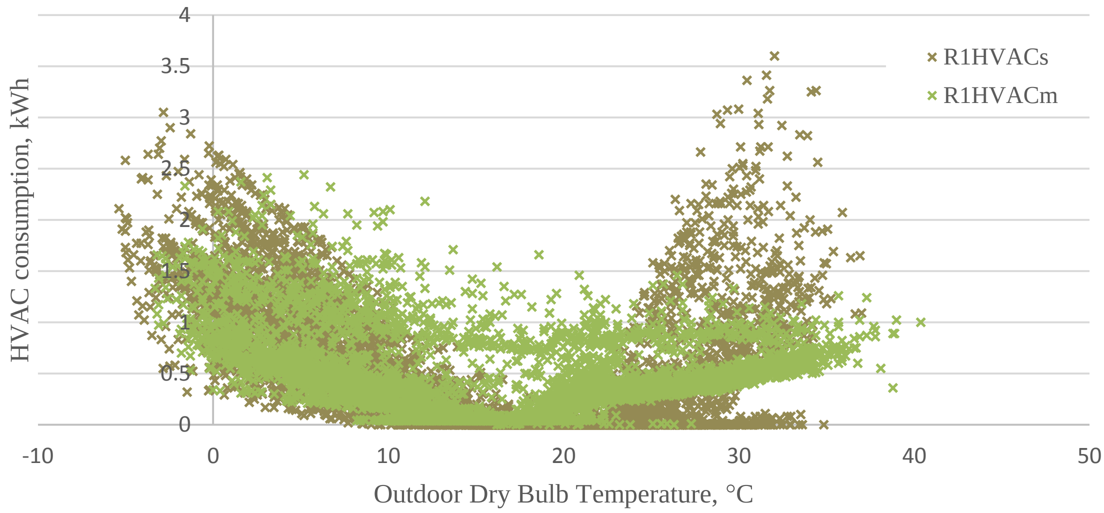


Figure 26: Residence 1 Energy Signature, hourly data, simulated (R1HVACs) vs monitored (R1HVACm).

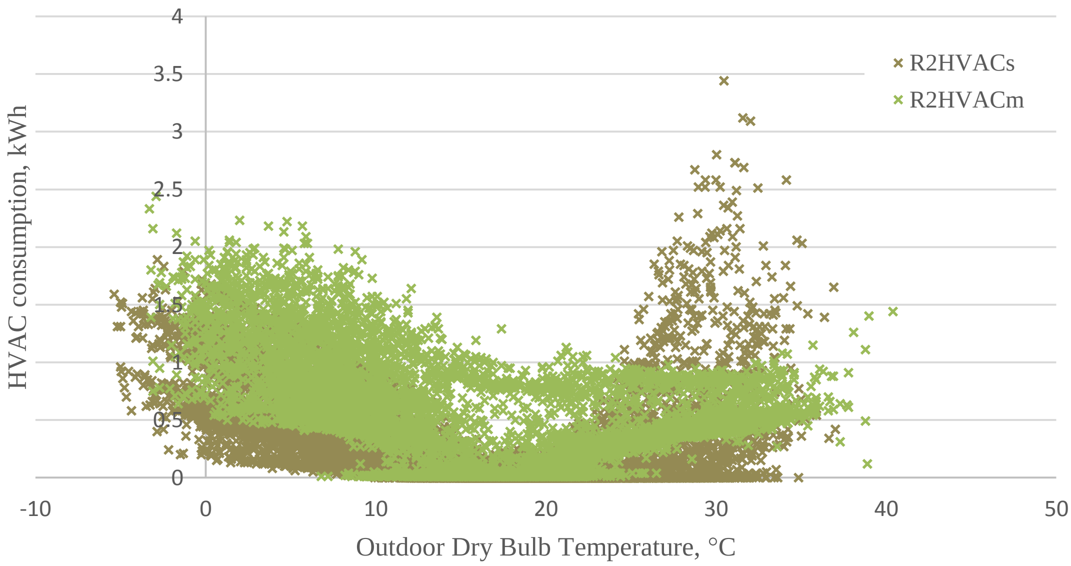


Figure 27: Residence 2 Energy Signature, hourly data, simulated (R2HVACs) vs monitored (R2HVACm).

The energy performance gap seems to be partly associated with the different actual building end-use compared to the expected behaviour [102]. At the design stage, indeed, standard occupant behaviour schedules [197] 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 behaviour.

In fact, the analysis of monitored indoor thermal conditions during the cooling season has revealed a trend of small fluctuations in room air temperatures throughout the day (Figure 28 and Figure 29). 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, 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 (Figure 28) and R2 (Figure 29). 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.

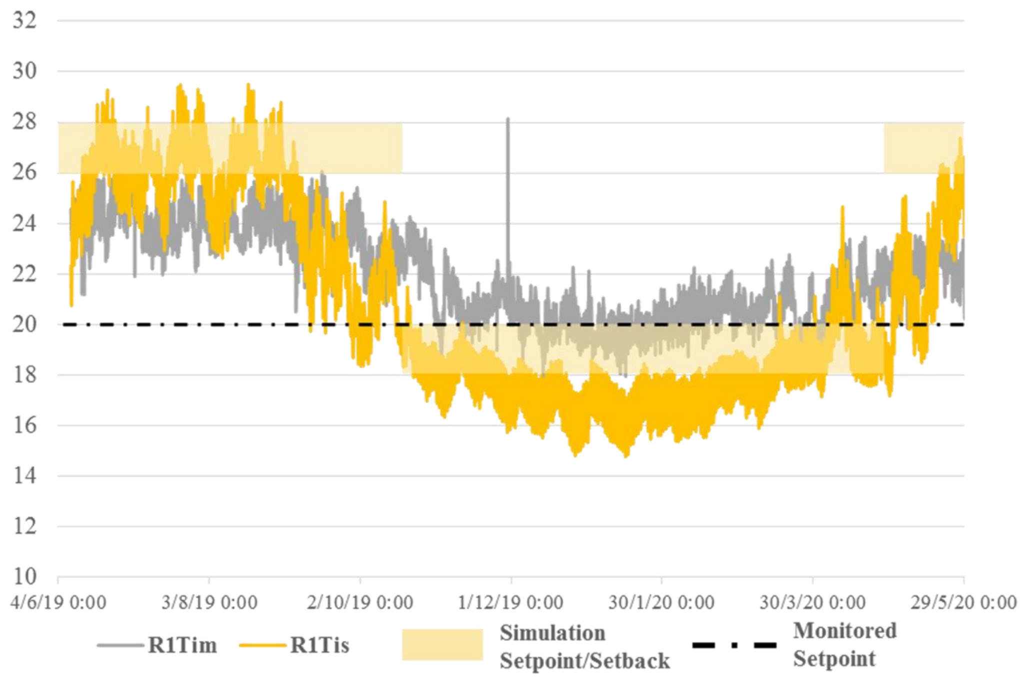


Figure 28: Indoor temperature of Residence 1 according to monitored data (R1Tim) and simulations (R1Tis), along with set-point/setback assumptions for simulations and actual set point during occupancy; hourly data for the period of June 2019 – May 2020.

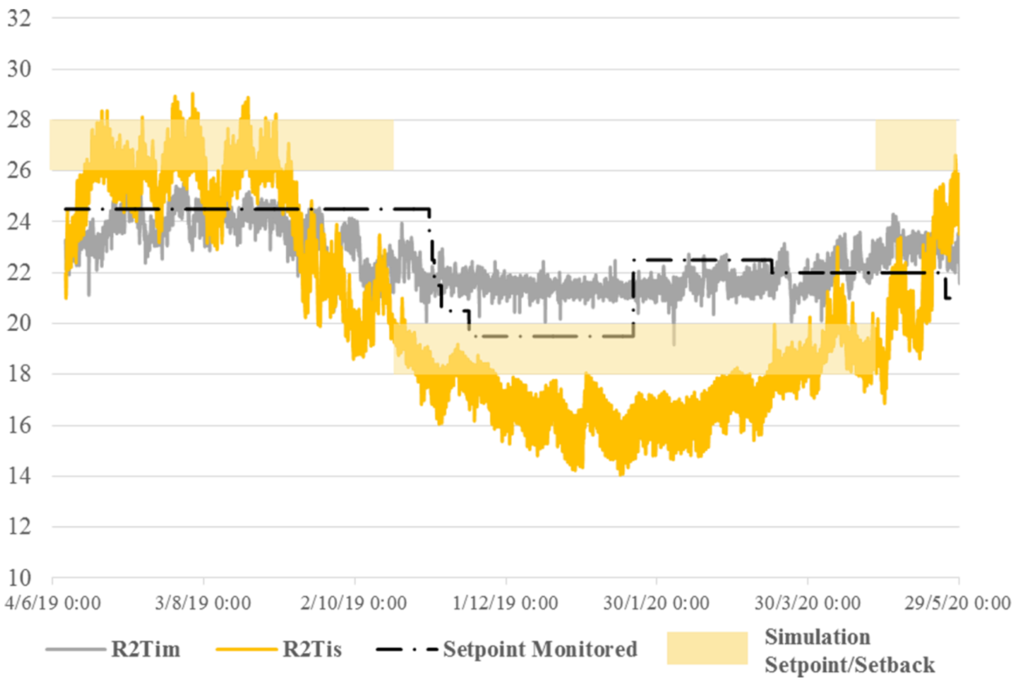


Figure 29: Indoor temperature of Residence 2 according to monitored data (R2Tim) and simulations (R2Tis), along with set-point/setback assumptions for simulations and actual set point during occupancy; hourly data for the period of June 2019 – May 2020.

As previously presented in Table 12 (section 6.2.2), 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.

6.3.2 Actual performance compared to design 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.

The assessment of the performance in relation to the design performance targets is presented in Table 14 where it is confirmed that despite the performance gap caused by unpredictable occupant behaviour, the actual performance has satisfied the design targets. The design targets focus on regulated energy consumption. The zero energy balance of the residences and the neighbourhood is assessed in the next section with the total consumption also taken into account.

Table 14: Performance of the residences and neighbourhood 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**

6.3.3 Zero Energy Balance

The case study is a "site renewable energy" neighbourhood currently composed of residential buildings and PV RES. Furthermore, its design performance targets focus on regulated energy and RES production. 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.

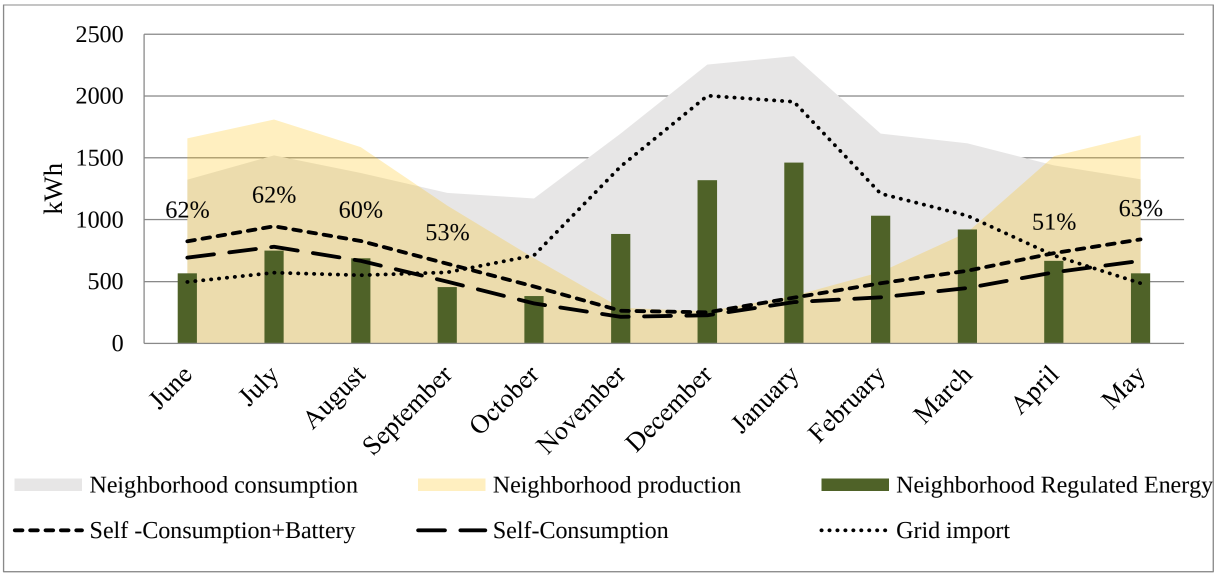


Figure 30: Monthly PV production against total consumption for the neighbourhood. Self-consumption represents energy produced by the PV that is consumed directly by the neighbourhood.

Between June 2019 and May 2020, the monthly production has exceeded the monthly consumption each month up to October, while from November to January, as expected, it is much lower (Figure 30 and Table 15). Production exceeds consumption again from April onward. In December and January, 87% of the production is directly consumed by the residences. However, this is enough to cover only a small portion of the total loads; 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 15 and Table 16 further illustrate how the balance varies within the year from month to month and from day to day as well as the contribution of the battery in consuming self-produced electricity and consequently reducing energy coming from the grid.

Table 15: 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.	Self-Cons./ PV Prod.	Self-Cons & Battery/ PV Prod.	Self-Cons & Battery/ Tot. Cons.	Self-Cons & Battery/ 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%

Table 16: Total PV Production/Total consumption per month and per day in each month. Legend: orange >100, ochre between 50 and 100, grey < 50

	2019							2020				
	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
M	125%	119%	115%	92%	59%	17%	12%	17%	34%	55%	105%	127%
1		119%	96%	101%	85%	24%	4%	15%	21%	13%	81%	113%
2		122%	114%	100%	44%	10%	6%	16%	12%	16%	87%	152%
3		106%	175%	88%	85%	15%	19%	16%	11%	19%	90%	107%
4		136%	173%	108%	93%	38%	17%	17%	25%	36%	98%	151%
5		127%	131%	114%	98%	15%	13%	18%	32%	39%	114%	132%
6		131%	155%	69%	80%	14%	17%	16%	33%	66%	105%	105%
7		108%	121%	133%	57%	39%	18%	12%	31%	30%	116%	167%
8	163%	116%	117%	45%	92%	16%	17%	14%	30%	68%	112%	144%
9	141%	78%	129%	133%	77%	32%	5%	17%	31%	52%	116%	152%
10	91%	123%	128%	133%	92%	31%	19%	18%	33%	50%	112%	145%
11	135%	138%	119%	140%	64%	4%	16%	19%	39%	79%	117%	103%
12	133%	141%	80%	112%	49%	2%	4%	18%	45%	64%	121%	117%
13	161%	139%	110%	110%	61%	23%	2%	16%	38%	63%	88%	83%
14	122%	149%	109%	116%	59%	23%	5%	13%	46%	38%	104%	89%
15	156%	48%	138%	90%	43%	6%	12%	12%	43%	69%	118%	107%
16	163%	157%	146%	99%	80%	15%	9%	15%	42%	67%	112%	90%
17	138%	148%	115%	97%	85%	19%	6%	19%	35%	70%	109%	120%
18	133%	101%	114%	66%	61%	19%	8%	1%	15%	71%	101%	103%
19	128%	127%	128%	39%	77%	10%	3%	15%	29%	96%	112%	106%
20	134%	156%	111%	95%	91%	10%	6%	19%	44%	75%	25%	85%
21	133%	135%	107%	126%	66%	18%	12%	19%	45%	91%	40%	130%
22	51%	109%	98%	18%	33%	17%	8%	20%	44%	47%	123%	122%
23	108%	123%	113%	24%	56%	8%	18%	20%	30%	70%	119%	137%
24	81%	117%	88%	96%	17%	21%	18%	17%	50%	63%	134%	139%
25	80%	101%	98%	69%	35%	22%	18%	3%	44%	23%	131%	156%
26	116%	114%	99%	99%	66%	26%	17%	14%	26%	11%	152%	167%
27	109%	82%	99%	83%	59%	5%	15%	24%	49%	21%	123%	162%
28	106%	73%	83%	73%	43%	10%	16%	16%	49%	84%	65%	122%
29	125%	121%	107%	88%	24%	16%	7%	27%	38%	89%	121%	127%
30	140%	117%	100%	82%	7%	9%	9%	28%		44%	124%	131%
31		111%	100%		6%		15%	22%		64%		149%

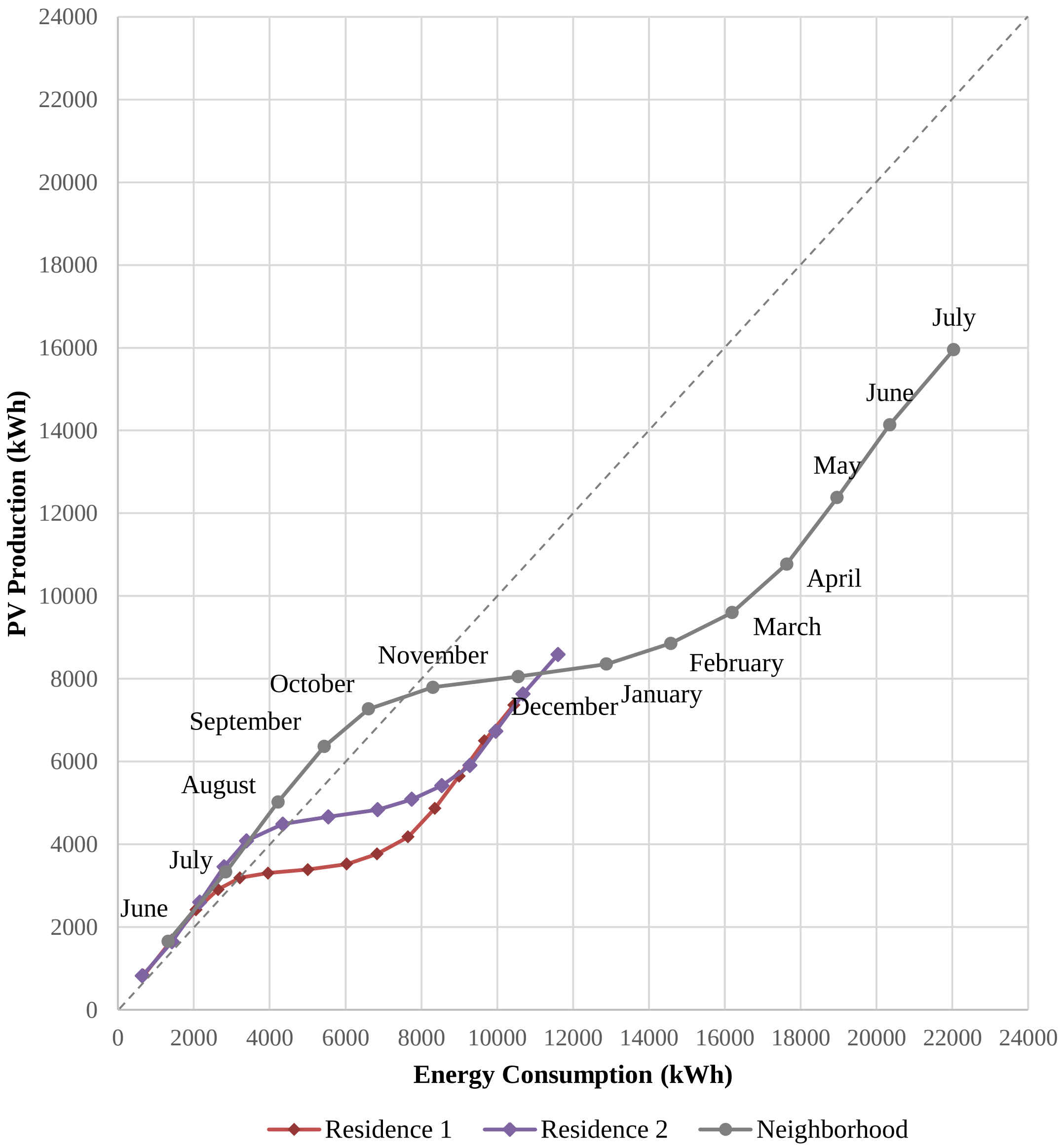


Figure 31: Cumulative energy consumption of the houses and the neighbourhood vs cumulative PV production during the period June 2019 – July 2020.

In Figure 31, the cumulative production and consumption of the houses and the neighbourhood, according to the measured data for the period of June 2019 – July 2020, are displayed. The neighbourhood appears to behave as a positive energy neighbourhood until October, whereas from November onwards it is a near-zero energy neighbourhood. Overall, the neighbourhood has achieved a positive energy balance on a yearly basis with regards to its regulated energy needs. 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%.

6.3.4 Investment cost and environmental 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 neighbourhood approach 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 CO2 reduction of the pilot ZEN compared to a neighbourhood designed and constructed according to the national standard are given in Table 17.

Table 17: 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 neighbourhood 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 [198].

[3]The household electricity price for Italy is 0.23€/kWh according to [199].

6.4 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 neighbourhood 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 neighbourhood. These results are obtained through an integrated approach to design and construction. The performance has been simulated and optimized at neighbourhood level, accounting also for microclimate conditions. 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% [87]). 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 neighbourhoods.

Regarding costs, the target for investment cost reduction was ≥ 16% compared to costs for a single ZEB of similar performance. Through the neighbourhood 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 investment cost refers to the technologies (energy saving, energy production, energy management, energy storage) that have been used to achieve the energy performance targets.

Planning for zero energy at the neighbourhood scale is a complex task that involves multiple actors and requires an integrated approach while also setting specific long-term goals for the design [39,168]. 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 [39]. 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 analysed in section 4 [200].

The occupants in particular are confirmed as critical stakeholders. On one hand, occupant behaviour and interaction with the building and its systems are a major source of the performance gap [52], [72]. 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 behaviour 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 neighbourhoods [37,200,201] especially in view of the raise of the future smart and clean energy communities [202], [203].

When considering the total consumption and total PV production of the neighbourhood for the first year, it has behaved as a positive energy neighbourhood for the first five months of monitoring, whereas for the remaining months it behaved as a near-zero energy neighbourhood. Overall the PV production during one year in the pilot neighbourhood can compensate for its regulated energy consumption. In this sense, the neighbourhood can be characterized as "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 neighbourhood was designed with a focus on regulated energy performance targets. Nonetheless, definitions exist that consider the total 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 neighbourhood in order to be a net zero energy neighbourhood.

PV production, in particular, can only partly be consumed directly in the neighbourhood 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 [73], [62]. 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 and the total consumption for five months, while per day the picture is also differentiated. 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 battery, 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 control operations, such as 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 [73], [70]. 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 [73], [204].

Monitoring installations for performance monitoring, evaluation, and energy management then become an indispensable component for the zero energy neighbourhood. 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.

7 ARTIFICIAL NEURAL NETWORKS FOR SMART ENERGY MANAGEMENT

7.1 Introduction

Installation of sensors, monitoring, and data gathering, followed by data processing, area the first substantial steps towards smartness; these are the steps that provide knowledge. In order to achieve smart management and the associated benefits, knowledge needs to be intelligently utilised. A major objective of the smart built environment is smart energy management and to this end, intelligence offered from forecasting algorithms is invaluable [14,142,205].

Load forecasting can be utilised for controlling charge and discharge of storage components [206], [207] that are integral to the smart grid as well as to the smart and zero energy buildings and communities, offering efficient energy management and reduced grid electricity loads [208], [209]. Depending on the forecasted period three types of forecasting are recognised [14,205]:

- Short-term forecasting: 1h to 1week for optimum
- Medium-term forecasting: 1week to 1year
- Long-term forecasting: 1year to decades ahead

Two methods for load forecasting are statistic mathematical models and artificial intelligence models [14,205]. ANN are artificial intelligence models used for forecasting providing high accuracy [14,205] and have been extensively used for short-term load forecasting [205,207]. In [210] a multi-layer perceptron neural network that uses load and weather data was applied in order to forecast the daily load of a suburban area, providing good prediction results. In [211] a feed forward artificial neural network for hourly demand prediction is tested and the proposed algorithm is able to achieve high prediction accuracy. In [212] ANN short-term forecasting has been integrated in a control algorithm aiming to manage battery charge/discharge for peak shaving of a power system operating in island mode.

The aim of this section is to investigate the development and application of a NARX ANN as a short-term forecasting tool in 2 case studies. The first case study is a micro-grid and the second case study is a concentrated solar power (CSP) system that is part of a solar field. Common objective of the two case studies is to develop accurate forecasting that can be utilised for efficient integration and operation of energy storage.

7.2 Case study 1: Leaf Community micro-grid

The Leaf Community micro-grid is located in Angeli di Rosora, Italy, Figure 32. Five buildings are currently connected to the micro-grid, all equipped with ground water heat pumps (GWHP). A 224kWh electrical storage system and a thermal storage with heat capacity 523.25kWh/K are also part of the micro-grid.

The energy production sources connected to the grid are:

- a micro-hydropower plant, of 48kWp,
- four rooftop PV installations of total 421.3kWp,
- a dual axis Solar Tracker of 18kWp.

All the previously mentioned power loads, renewables and storage components are connected in parallel to one single Point of Delivery (POD). All nodes as well as the collective operation of the micro-grid are monitored and controlled via the My Leaf web based platform.

The rooftop PVs are installed on four of the five interconnected buildings of the micro-grid. The production by each rooftop PV installation is consumed by the respective building first. If there is residual production, it is fed to the micro-grid. The production of the micro-hydropower plant is also fed to the micro-grid. When the production is not enough to cover the micro-grid's loads, energy is withdrawn from the main grid. Energy is also given to the main utility grid if the demand of the micro-grid has been fulfilled, storages are fully charged and there is excess production. Regarding the storages, both have been recently connected to the grid and their operation and integration are tested.

Figure 32: The Leaf micro-grid

The integration of the thermal storage with the micro-grid is of interest here. The thermal storage is connected to the building Leaf Lab and the automation system for its charge and discharge was set considering this building. Currently, the automation system is set to charge the thermal storage during weekends, when there is excess production from Leaf Lab's PV. This kind of automation will charge the storage while energy is not needed form Leaf Lab, but it could be needed from the micro grid. Consequently, there is a requirement to change the settings so that the thermal storage will be charged when there is real excess production at micro-grid level. To this end, excess production of the micro-grid during weekends needs to be predicted in a robust way so that charging of the thermal storage can be controlled accordingly.

7.2.1 System description

7.2.1.1 Ground water heat pumps

There are three water to water heat pumps (GWHP) in the Leaf Lab. GWHP1 is connected to the chilled beams installed in the offices for space heating and cooling.

GWHP2 and GWHP3 are connected to four HVAC units that service the offices, the laboratory and the warehouse. GWHP2 and GWHP3 are used for charging the thermal storage. When the thermal storage is discharged, thermal energy is provided to the chilled beams, thus avoiding activation of GWHP1 during the first three days of the week.

7.2.1.2 Thermal storage

The TES is a water tank with dimensions 12.3 X 11 X 3.4 m (400m^3).The water tank is buried and insulated with16 cm of XPS. The stored heat is sensible heat intended to cover the thermal loads of Leaf Lab. The thermal storage is charged during weekends using the excess production of the Leaf Labs' rooftop PV installation. The excess production is used to operate GWHP2 and GWHP3

7.2.1.3 System settings

The charging process begins when there is an excess in Leaf Lab's PV power production over 60kW. This is the threshold for activation of GWHP3. After activation of GWHP3, if there is excess of 50kW, GWHP2 is activated.

The activation of the heat pumps for charging the thermal storage is allowed only during weekends from 8:00am to 16:00pm in winter and in weekends from 7:00am to 18:00pm in summer. The pumps are switched off at the end of each schedule or if PV production is significantly reduced over a sustained period of time. In case PV power is instantly reduced power is withdrawn from the grid in order to keep the heat pumps, which provide heat to the thermal storage, activated. For the deactivation of the heat pumps if the power from the grid is greater than 130kW GWHP3 is switched off and following this GWHP2 is switched off when energy withdrawn from the utility grid exceeds 90kW.

7.2.2 Data

Power data as well as environmental data have been collected from the My Leaf platform. The power production of each energy source and the power taken from and exported to the main grid are measured.

The total production of the micro-grid is:

$$P_{MG} = P_{LLPV} + P_{AEAPV} + P_{SUMMAPV} + P_{KITEPV} + P_{TUV} + P_{HYDRO4} \quad (1)$$

Where:

P_{LLPV} is the power production of the Leaf Lab PV, in kW

P_{AEAPV} is the power production of the AEA PV, in kW

$P_{SUMMAPV}$ is the power production of the SUMMA PV, in kW

P_{KITEPV} is the power production of the KITE PV, in kW

P_{TUV} is the power production of the solar tracker, in kW

P_{HYDRO4} is the power production of the micro-hydro power plant, in kW

The production of the micro-grid is self-consumed and excess production is given to the main grid. Since there are measured data of the power exported to the grid, power production self-consumed at any time in the micro-grid can be calculated as follows:

$$P_{SC} = P_{MG} - P_{OUT} \quad (2)$$

Where:

P_{SC} is the power production self-consumed, in kW

P_{OUT} is the amount of excess power production that is fed to the main-grid, in kW

7.2.3 ANN model setup

The collected data is used for prediction of excess power of the micro-grid. There are two steps involved in this process. First a good prediction of excess production has to be achieved. For this purpose the Matlab [213] Neural Network (NN) tool is utilised. Alternative combinations of input parameters are tested so as to investigate which set of input parameters are suitable for achieving an accurate prediction of excess production.

7.2.3.1 Problem definition

The excess production of energy that can be used for charging the thermal storage can be determined from the measured data of power exported to the main grid. The prediction of excess production is a non-linear autoregressive problem. Past values of excess production as well as past values of day, time, irradiance, temperature and total production are used for prediction of excess power in 24h time horizon.

7.2.3.2 Input parameters

From equations (1) and (2) it can be deduced that excess production is related to parameters that determine production. For prediction of PV production, day of the week, time of day, temperature and radiation have been used as inputs [206], [214].

Prediction of hydro power production using as inputs the river water level and machine water level was attempted in [206] but a high accuracy prediction could not be achieved.

Table 18: Input data for each prediction

	Inputs	Target	Output
1st prediction	day of week time of day irradiance	excess production (P_{OUT})	excess production (P_{OUT})
2nd prediction	day of week time of day irradiance temperature	excess production (P_{OUT})	excess production (P_{OUT})
3rd prediction	day of week time of day micro-grid production	excess production (P_{OUT})	excess production (P_{OUT})

Three sets of input-output data have been tested (Table 18). As a first step, day of the week, time of day and irradiance is used for prediction of excess production. Subsequently, a second prediction approach is tested using the first step's inputs plus ambient air temperature as input. A third prediction model is attempted using as input parameters the day of the week, the time of the day and total micro-grid production. It can be observed from Figure 33 that excess production follows the trend of total production.

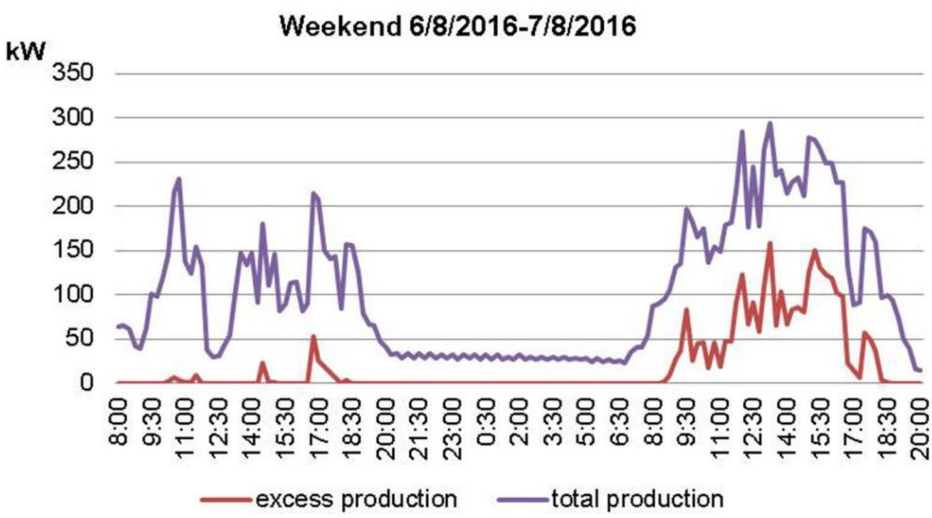


Figure 33: Excess production plotted along total production for the weekend 6/8 - 7/8 2016

7.2.4 Results

The prediction results of a neural network with 30 hidden neurons and 5 delays are presented below. For training the network the Lavenberg-Marquardt algorithm was used. The result of this process is the regression R that is achieved from training, validating and testing the ANN. A regression value close to 1 indicates that the network configuration is effective in providing highly accurate forecasts. All prediction models achieve good results with the second one providing the best prediction results.

The first prediction with inputs day of the week, time of day and irradiance could achieve a good training regression with R=0.96. A 2.5 month period of input data (3/5/2016-26/7/2016) was used for training, Figure 34.

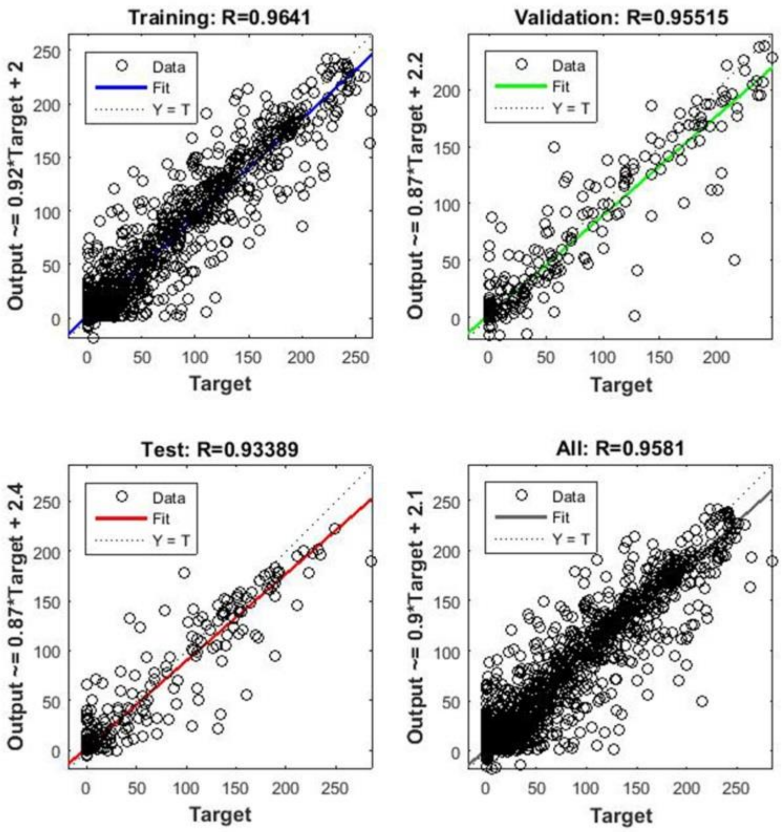


Figure 34: Prediction with irradiance input (data 3/5 - 26/7), 30 hidden neurons, 5 delays, Lavenberg-Marquardt algorithm

The second prediction with input day of the week, time of day, irradiance and temperature resulted in training regression of R=0.98, Figure 35. Because of some gaps in temperature data, one-month period was used for training, Considering that only one month data is used for this specific prediction configuration, it can be concluded that using as inputs irradiance and temperature along with day of week and time of day can produce highly reliable results.

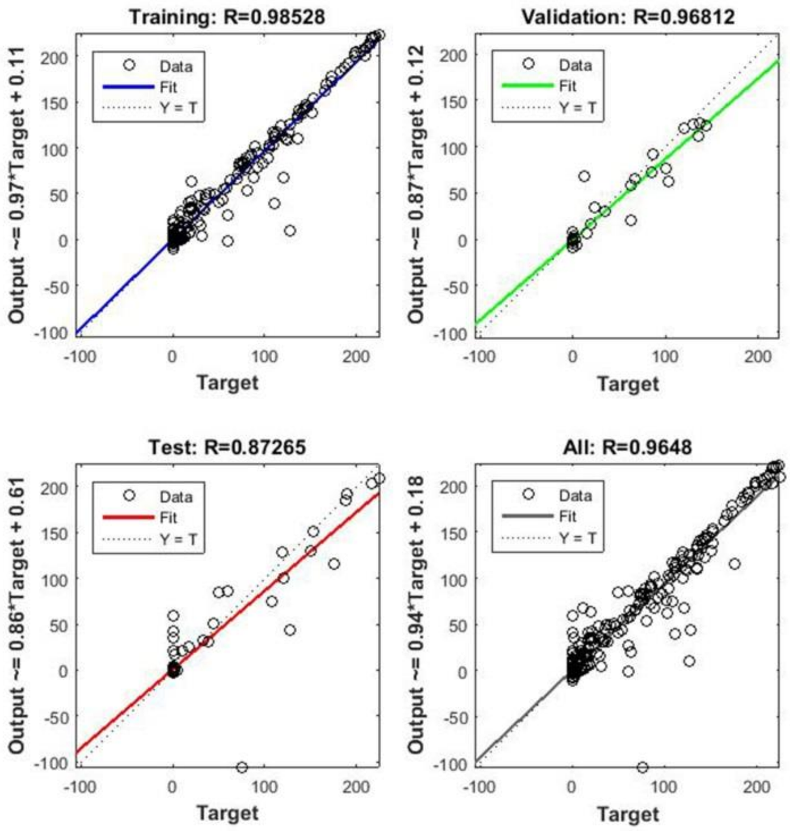


Figure 35: Prediction with irradiance and temperature input (data 23/1 - 29/2), 30 hidden neurons, 5 delays, Lavenberg-Marquardt algorithm

The third prediction with input day of the week, time of day and total micro-grid power production achieves training regression R=0.956, Figure 36.

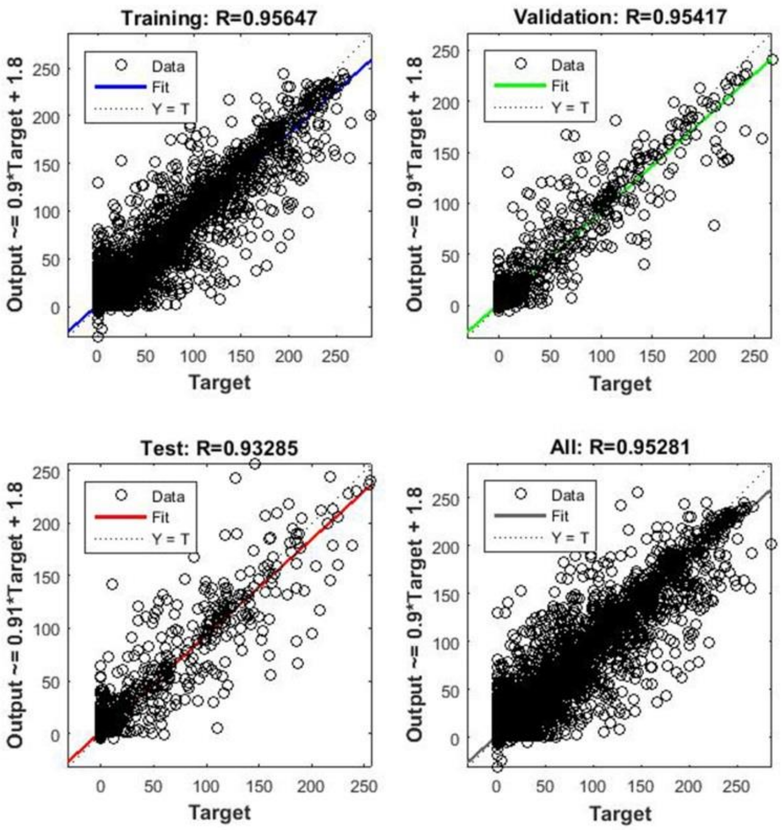


Figure 36: Prediction with production input (1 year data), 30 hidden neurons, 5 delays, Lavenberg-Marquardt algorithm

7.3 Case study 2: FRESCO CSP system

The FRESCO system is the basis for investigation as a second case study for developing ANN forecasting. The FRESCO system is based on Linear Fresnel Collector Concentrated Solar Power (CSP) technology. One of the system's advantages is its compact and light structure that makes it suitable for installation on flat roofs (Figure 37).

Figure 37: The FRESCO system installation on the NTL roof [103]

The FRESCO system is composed of:

- Linear Fresnel Reflectors
- Buffer storage
- Thermal Storage
- ORC (optional)

Its operation principle is based on the concentration of solar rays, by means of properly oriented high reflectivity mirrors, on a receiver tube in which a high temperature heat transfer fluid flows. The mirrors track the position of the sun throughout the day. The heated fluid when exiting the tube is stored into short-term buffer storage that allows to control production instabilities. Eventually, the produced thermal energy is collected at about 270°C and is stored inside a storage tank which can

(i) either heat buildings directly or

(ii) serve chillers for thermal energy transformation into cooling energy.

Moreover, the system can be connected to an Organic Rankine Cycle (ORC) unit so as to produce electricity[215].

The coupling of flat PV panels on the reverse side of the mirrors can introduce a very high flexibility in energy generation. When the direct solar irradiation is low (e.g. cloudy days) the mirrors are reverse and diffuse solar radiation is used to produce electricity by PV panels, thus increasing the contribution of the FRESCO production on electricity saving [103].

Being dependent on climatic parameters, FRESCO energy production may vary causing a mismatch between energy demand and production. Therefore, forecasting of production allows the design and implementation of management schedules depending on expected production, thus assisting towards a more efficient and secure operation both of the technology and the grid this is integrated in [216]. Here, the 24h forecasting of the thermal power production of the FRESCO system is investigated with the aim to achieve efficient management of the system and cover production intermittencies through controlled charge and discharge of a thermal storage. A 24h horizon prediction can also be valuable in managing hybrid solar installations where there is both electrical and thermal power production.

7.3.1 Data

The data that have been used for forecasting the thermal power production of FRESCO have been collected from the installation of the solar field installation that is located in Palermo (Figure 38).

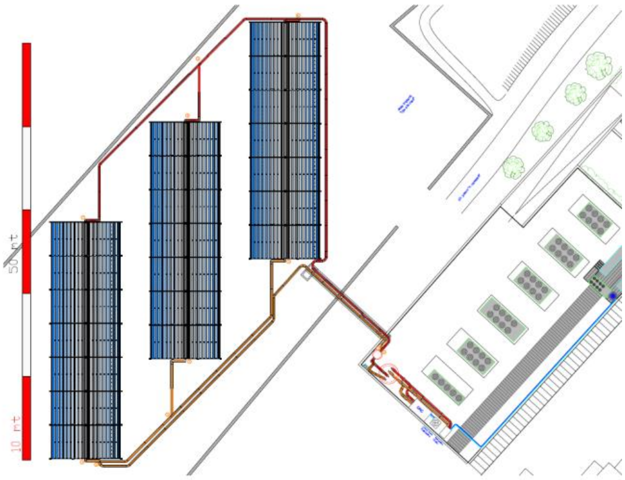


Figure 38: General plan of the solar field in Palermo with three parallel rows of linear fresnel collectors [215]

The data are measured per five seconds and include the following:

- T (in): temperature of the oil at the beginning of the absorption pipe
- T (out): temperature of the oil at the end of the absorption pipe
- Q: flow of the oil
- DNI: Direct normal irradiance
- T (amb.): Ambient air temperature
- Wind speed

From the above measured data are calculated:

- The focalization/defocalization state of the mirrors

- The thermal power of the system
- The efficiency of the system

For the creation of the dataset that was used for the forecasting, the measured values per minute were used and the intermediate values per second were filtered out.

Furthermore, if the value of Q was below 0.1, this was an indication that the system was not operating. Thus, the days that Q<0.1 during operating hours of the system, were removed from the dataset. Among these days were also the weekends and holidays during which the system was not working.

Two datasets were collected eventually:

1. Dataset containing 40 days of May-June-July 2017 (19 days of May, 8 days from June and 13 days of July)
2. Dataset containing 32 days of September-October-November (14 days of September, 16 days of October, 2 days of November)

7.3.2 ANN model setup

The forecasting of the thermal power production is the subject of this case study. Similarly to the 1st case study, the thermal power forecasting was solved as a non-linear autoregressive problem. Past values of thermal production as well as past values of the parameters that are used for the calculation of and affect the thermal power production were used for forecasting the thermal power (Table 19) in 24h horizon.

Table 19: Input and target data used for prediction

<table>
<tr><th>Inputs</th><th>Target</th><th>Output</th></tr>
<tr><td>day of week</td><td rowspan="8">thermal power</td><td rowspan="8">thermal power</td></tr>
<tr><td>time of day</td></tr>
<tr><td>temperature of the oil at the beginning of the absorption pipe</td></tr>
<tr><td>temperature of the oil at the end of the absorption pipe</td></tr>
<tr><td>flow of the oil</td></tr>
<tr><td>DNI</td></tr>
<tr><td>Ambient air temperature</td></tr>
<tr><td>Wind speed</td></tr>
</table>

In the 1st case study, for forecasting the excess power production of the Leaf lab micro-grid, a neural network structure with 30 hidden neurons and 5 delays gave the best prediction results and the Lavenberg-Marquardt algorithm was used for training the network [217]. This configuration was used in the present case study as well. Moreover, 70% of the input data were used for training the neural network, 15% for validating and 15% for testing the prediction. Again, the Neural Network Toolbox of Matlab was employed for this process.

Apart from the regression value R that is achieved from training, validating and testing the ANN, a comparison of the actual with the predicted values could give a deeper insight in the forecasting results that are achieved. For that purpose, the code script of Matlab that was used for training, validating and testing the network was accessed and edited so as to produce the predicted values and plot them along the actual values.

Alternative ANN structures were also considered in order to evaluate the influence of the hidden neurons and the delays in the forecasting accuracy of the ANN, Table 20.

Table 20.Alternative ANN structures

	ANN1	ANN2	ANN3	ANN4	ANN5
delays	1	1	2	2	5
hidden neurons	10	30	10	30	30

7.3.3 Results

First the structure that had been developed in the 1st case study was used for training. The training of the network with 30 hidden neurons and 5 delays (ANN 5) for both data series resulted in satisfactory prediction results achieving a good regression.

The first dataset containing data form May, June and July 2017 resulted in a good overall regression R=0.977, Figure 39.

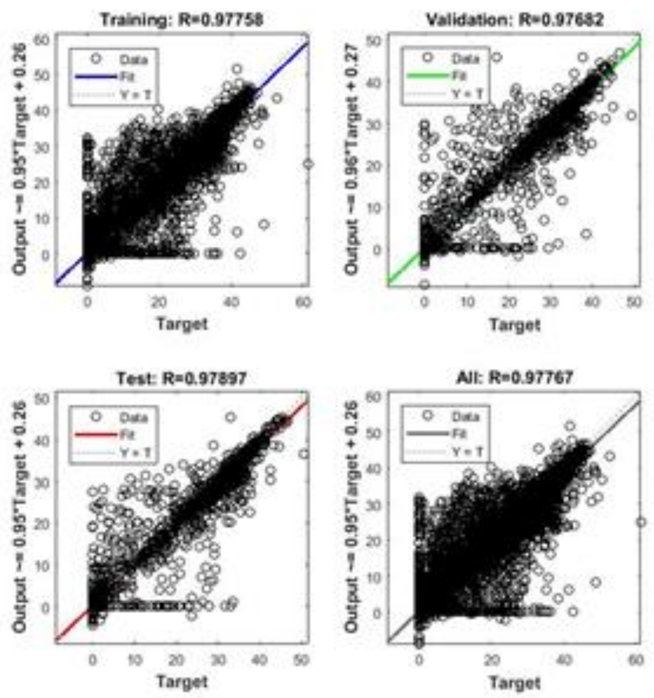


Figure 39: Regression results for the dataset May-July 2017

The second dataset containing data form September, October and November 2017 resulted in an overall regression R=0.985, Figure 40.

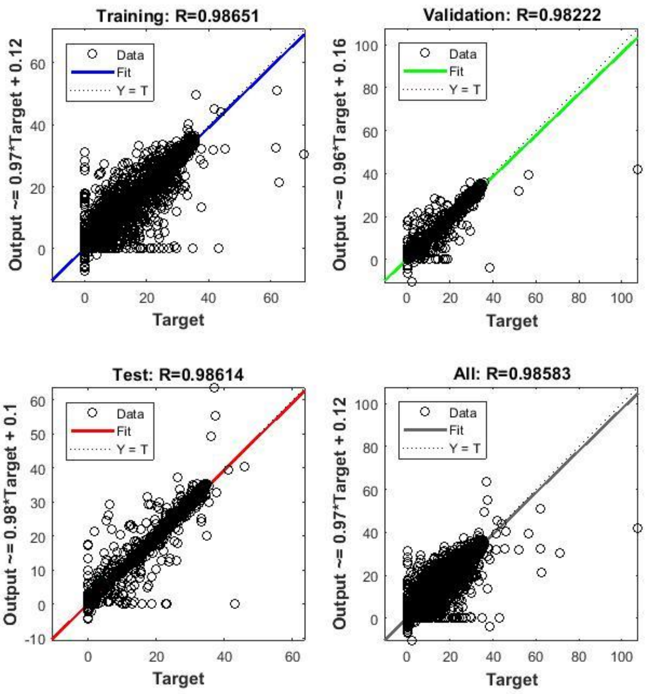


Figure 40: Regression results for the dataset September-November 2017

Obtaining a good regression is indicative that reliable forecasting can be achieved. However, dispersion of data away from the regression line is noticeable, especially in Figure 39. Therefore, comparison of the actual to the predicted values gave a deeper insight in evaluating the developed ANN.

In Figure 41 are illustrated the actual thermal power data and the predicted values for the dataset May-July. In Figure 42 one day from the period May-July is plotted.

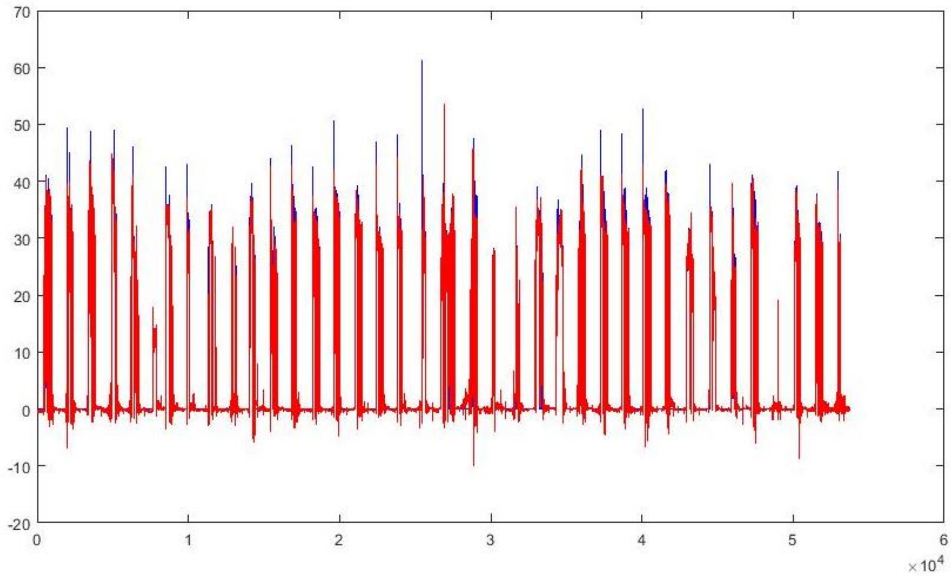


Figure 41: Actual thermal power (blue) plotted against predicted thermal power (red), ANN with 30 hidden neurons and 5 delays, May-June dataset

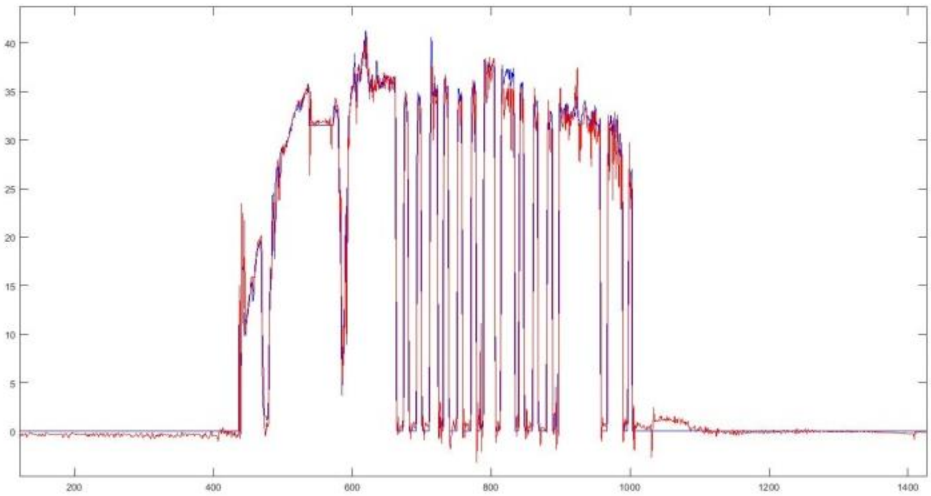


Figure 42: Actual thermal power (blue) plotted against predicted thermal power (red), ANN with 30 hidden neurons and 5 delays, 1 day from May-June dataset

In Figure 43 are illustrated the actual thermal power data and the predicted values for the dataset September-November. In Figure 44 one day from the period September-November is plotted.

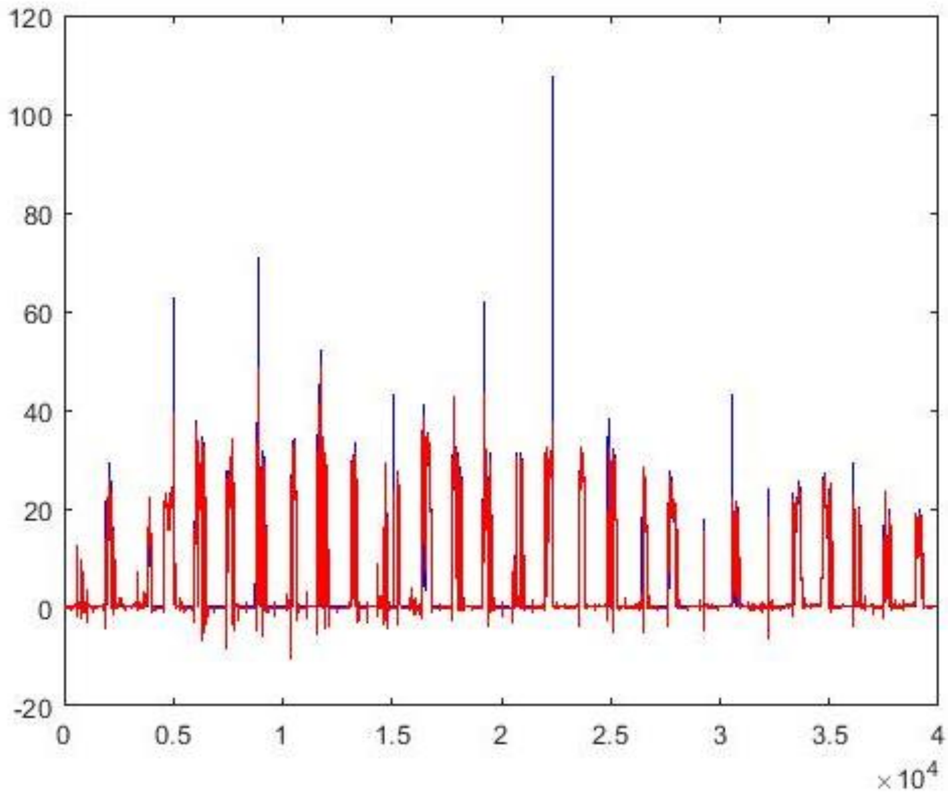


Figure 43: Actual thermal power (blue) plotted against predicted thermal power (red), ANN with 30 hidden neurons and 5 delays, September-November dataset

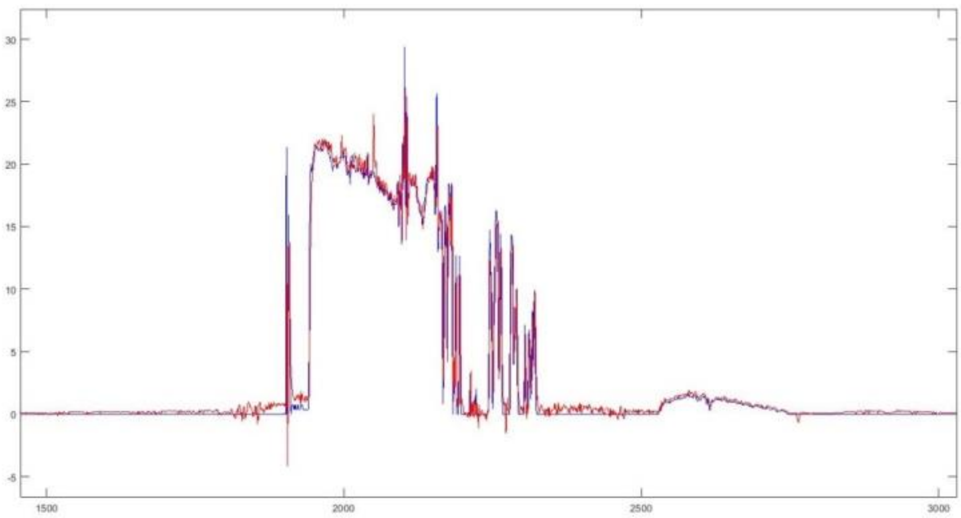


Figure 44: Actual thermal power (blue) plotted against predicted thermal power (red), ANN with 30 hidden neurons and 5 delays, 1 day of September-November dataset

The results indicate that the forecasted values follow closely the actual values of thermal power. However, errors are also visible. For that purpose the errors were evaluated by calculating the Mean Bias Error (MBE) and the root mean square error (RMSE).

In Table 21 and Table 22 are presented the MBE and RMSE as well as the regression value R for the various ANN that were studied. The second dataset presents better results, but this is the smaller dataset, therefore it is expected that errors will be less than the errors that appear in a larger and thus more representative dataset.

Table 21: Evaluation of ANN forecasting accuracy (dataset May-July)

	ANN1 10-1	ANN2 30-1	ANN3 10-2	ANN4 30-2	ANN5 30-5
MBE	0.03	0.029	0.09	0.04	0.018
RMSE	3.09	3.05	2.60	2.50	2.59
R	0.963	0.964	0.973	0.974	0.977

Table 22: Evaluation of ANN forecasting accuracy (dataset September-November)

	ANN1 10-1	ANN2 30-1	ANN3 10-2	ANN4 30-2	ANN5 30-5
MBE	-0.013	-0.018	0.049	0.049	0.0127
RMSE	1.71	1.70	1.60	1.60	1.57
R	0.982	0.982	0.983	0.984	0.986

Overall good R values and RMSE values are achieved with all ANN structures. It is also observed that increasing the number of delays improves the performance of the network, whereas increasing the number of neurons does not change the performance of the network. It can be concluded that a simple structure network with 10 hidden neurons and 2 delays can produce results similar to the network with 30 hidden neurons and 5 delays, for the considered forecasting problem.

In Figure 45 are illustrated the actual thermal power data and the predicted values for the dataset May-July for the ANN structure with 10 hidden neurons and 2 delays.

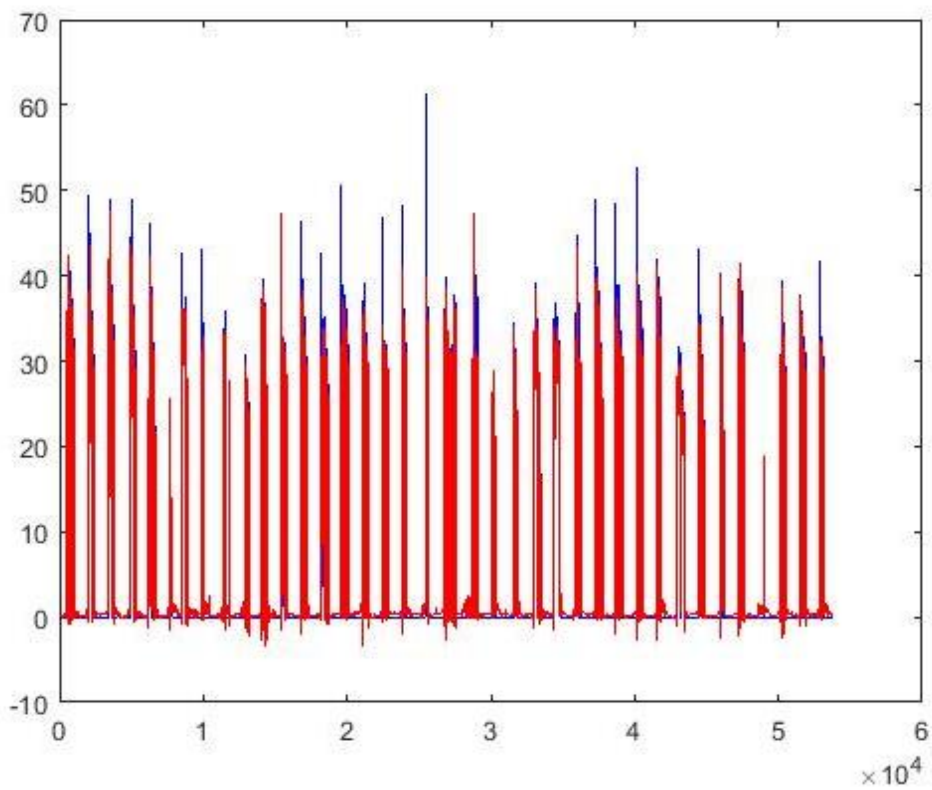


Figure 45: Actual thermal power (blue) plotted against predicted thermal power (red), ANN with 10 hidden neurons and 2 delays, May-July dataset

In Figure 46 one day from the period May-July is plotted for the ANN with 10 hidden neurons and 2 delays.

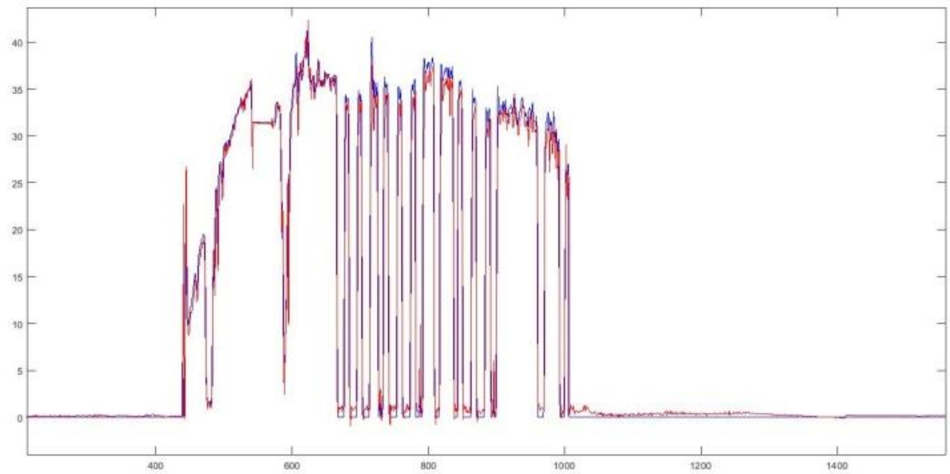


Figure 46: Actual thermal power (blue) plotted against predicted thermal power (red), ANN with 10 hidden neurons and 2 delays, 1 day from May-July dataset.

One major parameter that affects the thermal power of the network but cannot be measured or considered in the forecasting problem is the dust. In addition to dust, shadowing and blocking effects between mirrors as well as solar tracking accuracy can affect the thermal power production. Therefore, it is possible that the errors in the forecasted values are due to these parameters that could not be included in the forecasting problem.

7.4 Discussion

7.4.1 Discussion of ANN training results

Having a reliable 24 hours forecasting model provides the basis for the design and implementation of advanced dynamic integrated control.

The first case study work focuses on the thermal storage integration with the Leaf micro-grid. Specifically, the forecasting of excess power production that can be used for charging the storage is of interest. The forecasted output is aimed at scheduling the process of charging thermal storage during weekends or other time intervals when excess power is significant and may be utilised by the micro-grid rather than exported into the main power grid. In this direction, 24h excess power production forecasting of the Leaf micro-grid has been investigated using Neural Network Lavenberg-Marquardt algorithm.

In the Leaf micro-grid there is PV-power production and hydro-power production. Despite not using input data related to hydro-power production, a robust and highly accurate forecasting has been achieved for various seasons using measurements of the environmental parameters of irradiance and temperature as inputs. Having achieved a reliable forecasting, an appropriate control can be designed for optimum utilisation of the prediction. Based on the requirement for 60kW for activation of the first heat pump, this can be the first threshold of excess power production of the micro-grid. The control system will have to take into account POD power levels where excess power is measured. The control will also include an evaluation of the amount of time that excess production is over the thresholds. A decision making mechanism will guide the charging of the thermal storage based on available excess production and hours of availability during weekends. The target of the control will be the cost efficient integration of the thermal storage in the micro-grid.

The power of the developed forecasting algorithm has been investigated in the second case study towards forecasting of the thermal power of the system FRESCO CSP. The ANN with 30 hidden neurons and 5 delays has been used for forecasting the thermal power of FRESCO 24h ahead and good regression values were obtained from training, testing and validating the network. Besides, alternative ANN structures have been also investigated and it was concluded that for the considered forecasting problem a simple ANN structure with 10 hidden neurons and 2 delays can provide equally accurate results.

Forecasting errors are unavoidable though and these should be considered when applying the prediction in real conditions for system management. It is highly possible that the errors are due to the parameter of dust that affects the system's production. Unfortunately, dust is not a parameter that can be measured. In the FRESCO case, the forecasting can be used for decision making in optimizing the system's operation and energy management. Forecasting the thermal power one day ahead will allow decision making regarding the charging and discharging of the thermal storage based on the forecasted thermal power production. A 24h horizon prediction can also be valuable in managing the hybrid solar installation where there is both electrical and thermal power production.

7.4.2 Link to the Zero Energy Neighbourhood

Building on observations and knowledge obtained from the two case studies, the ANN forecasting can be investigated for the ZEN. In that case a specific control problem needs to be formulated from the management point of view. This could concern HVAC demand forecasting per residence, providing feedback and operation suggestions to occupants. On a higher level, total electricity demand of the community can be forecasted for managing battery charge and discharge targeting at increasing power autonomy. Research findings from multi-family buildings reveal that forecasting gives better results at floor level compared to apartment level [218]. Similarly when considering a residential area, optimum aggregation level of residential units, can be investigated.

Finally, considering the monitoring and data recording interruption that occurred in the pilot ZEN (details in Annex II), the question is raised on how forecasting, and consequently energy management and control can be achieved in lack of data for long periods.

8 Conclusion

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 race against climate change and in particular in the decarbonisation of the energy landscape.

The present thesis analysed and discussed a comprehensive, integrated approach for neighbourhood level implementation of the zero energy concept. The measured performance evaluation of a pilot ZEN proves that zero energy performance with reduced investment costs compared to single ZEBs is achievable following an integrated design, construction, and monitoring methodology. Finally, the potential of forecasting models in support of smart energy management has been investigated.

Viewing concurrently the major topics discussed in this thesis, the following relations can be highlighted (Figure 47): Integration, measurement and verification, and smart all link to the creation of the zero energy built environment. Monitoring is necessary for M&V and sets the ground for the smart capabilities of the built environment. Simultaneously, the smart design is part of an integrated design process; the beginning for highlighting this relation is made here by showing how the M&V planning and implementation is placed in an IDP framework

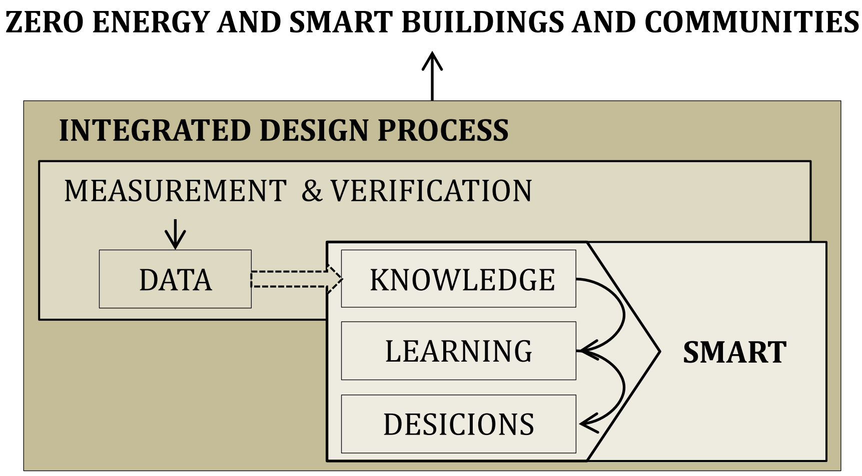


Figure 47: The thesis topics placed in a connecting framework

8.1 Contribution

8.1.1 Integrated Design Process roadmap for Zero Energy Communities

The thesis presented an integrated design process roadmap for Zero Energy Communities that has been fully implemented and is applicable and adaptable in multiple contexts. Furthermore, the stakeholder links and interactions that are critical to the implementation of the process have been highlighted. Thus the thesis has contributed by expanding existing knowledge and background on the IDP.

The lessons learnt from the implementation of 4 pilot ZEN have offered insights on the composition and function of the integrated team of stakeholders. A non-exhaustive list of stakeholders that are involved in the ZEN implementation has been presented divided in internal and external stakeholders. Establishment of an integrated project management structure that will ensure the coordination and integration of the stakeholders from the very beginning, by establishing roles, sub-teams and clear communication links, is unequivocal, yet challenging in lack of experience.

8.1.2 Novel, integrated framework for Measurement and Verification

The thesis has presented a novel, integrated framework for Measurement and Verification of zero energy buildings and communities that has been developed and implemented in four pilot ZENs along their integrated design process.

The M&V is integral to the design and operation of a high-performing built-environment and he novel comprehensive M&V framework has been integrated into an iterative project management flow, deploying technical guidance from established M&V protocols and governed by quality control. Having been tested through implementation, it can be used as guidance for similar future neighbourhood projects, but its applicability is not necessarily limited to neighbourhoods.

For new-built projects in the era of zero energy buildings and communities, where the IDP has emerged as the proposed approach for achieving the seamless design, construction, and operation of buildings, the M&V needs to be viewed as part of the project management and development process.

The proposed framework can be useful to project managers for integrating M&V into the project management and explicitly aligning it with the project development stages into an Integrated Design and Delivery process.

8.1.3 Zero Energy Neighborhood measured performance

The thesis has further contributed by analysis and discussing actual performance data that currently are scarce in literature.

The measured performance results of a pilot ZEN in Italy, from its first year of monitoring, have shown that the pilot neighbourhood 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 neighbourhood, the first five months of monitoring starting from the beginning of summer, it has achieved a positive balance. Overall, the neighbourhood has achieved a positive energy balance on a yearly basis for its regulated energy needs, which matches the EPBD definition of the near zero energy buildings when extended to the neighbourhood level.

8.1.4 Artificial Neural Networks as a stepping stone to smartness

The thesis has demonstrated that Artificial Intelligence is a stepping stone to smartness. Artificial Intelligence solutions for smart management exist that can be developed and implemented within a holistic, integrated planning for smart energy management.

Recognising the first two preparatory steps in data collection and data processing respectively, the next step – and substantial to developing smart management and control – is learning that can be achieved with forecasting models.

Short-term ANN forecasting models with high forecasting accuracy have been developed for a micro-grid energy community (training regression R=0.98) as well as for a CSP system within a solar field (training regression R=0.97) with common objective to utilise the forecasting for optimising the integration and control of storage. Development of forecasting models is guided by specific control objectives, therefore considering a zero energy community, forecasting models can be developed for the community demand, per residence or at community level, considering its regulated or total demand, depending on the management objectives.

8.2 Further research

Common theme for discussion for all topics is the role of humans, either as occupants or users or citizens. The analysis and results of the present work have discussed the occupant/user as a stakeholder in the design and operation of zero-energy and smart buildings and communities. Nevertheless, the role of humans as citizens when discussing the city scale shall be included in the stakeholder group and interactions. There is an open field for further research on occupant engagement and training and the interaction and perception of occupants residing in zero energy and smart buildings and communities.

With respect to occupant comfort, a thorough analysis of the indoor environmental quality data, including thermal comfort, visual comfort and air quality data, linked to the POE survey results is also part of further research for a complete evaluation of the in use performance. This can be complemented by actual microclimate analysis data and relevant observations on the actual impact of the implemented microclimate interventions on both IEQ and energy performance.

More results from realized projects are needed for further boosting the uptake of the zero energy and smart concept at neighbourhood scale and paving the way to future clean energy neighbourhoods. This includes standardisation of the integrated design and integrated project delivery. Extended and specialised technical knowledge exists for all of the topics discussed but integration and implementation of the existing knowledge seems to be a significant challenge to realising zero energy and smart buildings and districts.

In view of the rise of Building Information Modelling, the potentialities and challenges of implementation of the integrated design process fully supported by BIM offer opportunities for further research. BIM presents a collaborative platform and the respective tools on which all involved stakeholders can collaborate for implementing an integrated design process and project delivery. However, architects are challenged by using CAD and recently BIM tools in the conceptual design stages, since it can be seen as limiting to the creative process. A question is raised on what can be the role of BIM in the conceptual design stages and how its potential can be exploited at these stages.

Considering that the integrated design process is holistic, it involves both well-defined problems, such as clear environmental targets, but also ill-defined problems such as the architectural design process itself. While the environmental/energy targets can be optimally solved and achieved following a roadmap of iterative steps, which could be supported by BIM and simulations throughout the process, what does this mean for the architectural design process? As ill-defined, the architectural design process can give multiple results through different thinking processes, how are then architectural design and zero-energy design optimally integrated?

For the smart built environment it is imperative to consider who has the control. Some operations and decisions can be automated (automated intelligence), but some others need to be left to the occupants while providing them with options, this would be integration of the artificial intelligence with the human intelligence, leading to what can be called “integrated intelligence”. There is room for studying the implementation of integrated intelligence from the building to the city level.

Finally, there is an open path for viewing the topics discussed herein, and adjusting accordingly their implementation, from the renovation perspective.

8.3 Limitations

The limitations can be summarized as follows:

- Out of the 4 pilot neighbourhoods, only 3 could provide feedback for the involved stakeholders and their interactions. This is a small sample for drawing general conclusions for the zero energy community implementation. However the results and observations have been counterchecked with the literature on projects of similar context and literature on the IDP.
- Recognizing the limitations of the proposed M&V framework, it is expected that it can be subject to cost, time, and/or human resources constraints. This is also

true for the IDP overall. It is expected that adjustments are applicable relevant to the project scale and objectives.

- The pilot ZEN in Italy is composed of 2 buildings and is a new development. The approach is transferable to bigger neighbourhoods as well as to existing neighbourhoods and implementation with subsequent results from diverse developments will help study the transferability of this approach in practice.
- The measured performance results of the pilot ZEN have been obtained from its first year of monitoring. Further monitoring results will help evaluate the performance of the ZEN in the long-term and form robust decisions for drawing its energy management direction.
- 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” neighbourhood 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.
- The measured performance analysis of the neighbourhood does not include a thorough analysis of IEQ measurements. These are essential for a complete evaluation of the in-use performance and have been suggested to be subject of further research.
- Accurate short-term forecasting models have been developed for two cases. However these have remained at theoretical development stage.

REFERENCES

[1] European Commission, The European Green Deal, Eur. Comm. (2019). doi:10.1017/CBO9781107415324.004.

[2] The Paris Agreement | UNFCCC, (n.d.). https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement (accessed January 31, 2021).

[3] Global Alliance for Buildings and Construction International Energy Agency and the United Nations Environment Programme, 2019 Global Status Report for Buildings and Construction - Towards a zero-emissions, efficient and resilient buildings and construction sector, 2019. https://globalabc.org/our-work/tracking-progress-global-status-report (accessed July 12, 2020).

[4] United Nations, The New Urban Agenda - Habitat III, 2017. https://habitat3.org/the-new-urban-agenda/ (accessed May 4, 2021).

[5] J. Laustsen, Energy Efficiency Requirements in Building Codes , Energy Efficiency Policies for New Buildings, 2008. doi:10.1.1.378.1012.

[6] 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.

[7] C. Flurin, Eco-districts: Development and Evaluation. A European Case Study, Procedia Environ. Sci. 37 (2017) 34–45. doi:10.1016/j.proenv.2017.03.012.

[8] 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.

[9] A. Blumberga, R. Vanaga, R. Freimanis, D. Blumberga, J. Antužs, A. Krastiņš, I. Jankovskis, E. Bondars, S. Treija, Transition from traditional historic urban block to positive energy block, Energy. 202 (2020) 117485. doi:10.1016/j.energy.2020.117485.

[10] O. Lindholm, H.U. Rehman, F. Reda, Positioning positive energy districts in European cities, Buildings. (2021). doi:10.3390/buildings11010019.

[11] B. Gagnon, R. Leduc, L. Savard, From a conventional to a sustainable engineering design process: Different shades of sustainability, J. Eng. Des. 23 (2012) 49–74. doi:10.1080/09544828.2010.516246.

[12] G. Löhnert, A. Dalkowski, W. Sutter, Integrated Design Process - a Guideline for sustainable and solar-optimized building design, IEA Task 23 Optimization of Solar Energy Use in Large Buildings Subtask B Design Process Guidelines, Berlin / Zug, 2003. http://task23.iea-shc.org/publications.

[13] M.W. Ahmad, M. Mourshed, D. Mundow, M. Sisinni, Y. Rezgui, Building energy metering and environmental monitoring - A state-of-the-art review and directions for future research, Energy Build. 120 (2016) 85–102. doi:10.1016/j.enbuild.2016.03.059.

[14] A.R. Khan, A. Mahmood, A. Safdar, Z.A. Khan, N.A. Khan, Load forecasting, dynamic pricing and DSM in smart grid: A review, Renew. Sustain. Energy Rev. 54 (2016) 1311–1322. doi:10.1016/j.rser.2015.10.117.

[15] I. Colak, S. Sagiroglu, G. Fulli, M. Yesilbudak, C.F. Covrig, A survey on the critical issues in smart grid technologies, Renew. Sustain. Energy Rev. 54 (2016) 396–405. doi:10.1016/j.rser.2015.10.036.

[16] IPEEC Building Energy Efficiency Taskgroup Zero Energy Building Definitions and Policy Activity An International Review, n.d.

[17] 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.

[18] 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.

[19] 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:doi:10.3000/17252555.L_2010.153.eng.

[20] METI-Ministry of Economy Trade and Industry, METI Compiles ZEB Roadmap, (2015). https://www.meti.go.jp/english/press/2015/1217_02.html (accessed May 12, 2020).

[21] BPIE, Nearly Zero Energy Buildings definitions across Europe, 2015. http://bpie.eu/publication/nzeb-definitions-across-europe-2015/ (accessed March 18, 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] 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.

[24] 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.

[25] 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.

[26] K. Schiel, O. Baume, G. Caruso, U. Leopold, GIS-based modelling of shallow geothermal energy potential for CO2 emission mitigation in urban areas, Renew. Energy. 86 (2016) 1023–1036. doi:10.1016/j.renene.2015.09.017.

[27] J.-H. Kim, H.-R. Kim, J.-T. Kim, Analysis of Photovoltaic Applications in Zero

Energy Building Cases of IEA SHC/EBC Task 40/Annex 52, Sustainability. 7 (2015) 8782–8800. doi:10.3390/su7078782.

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

[29] P. Torcellini, D.B. Crawley, Understanding Zero-Energy Buildings, ASHRAE J. (2006).

[30] P. Torcellini, S. Pless, M. Deru, Zero Energy Buildings: A Critical Look at the Definition, 2006.

[31] M. Kapsalaki, V. Leal, M. Santamouris, A methodology for economic efficient design of Net Zero Energy Buildings, Energy Build. 55 (2012) 765–778. doi:10.1016/j.enbuild.2012.10.022.

[32] J. Kurnitski, A. Saari, T. Kalamees, M. Vuolle, J. Niemelä, T. Tark, Cost optimal and nearly zero (nZEB) energy performance calculations for residential buildings with REHVA definition for nZEB national implementation, Energy Build. 43 (2011) 3279–3288. doi:10.1016/j.enbuild.2011.08.033.

[33] M. Hamdy, A. Hasan, K. Siren, A multi-stage optimization method for cost-optimal and nearly-zero-energy building solutions in line with the EPBD-recast 2010, Energy Build. 56 (2013) 189–203. doi:10.1016/j.enbuild.2012.08.023.

[34] A.J. Marszal, P. Heiselberg, Life cycle cost analysis of a multi-storey residential Net Zero Energy Building in Denmark, Energy. 36 (2011) 5600–5609. doi:10.1016/j.energy.2011.07.010.

[35] D. Kim, H. Cho, J. Koh, P. Im, Net-zero energy building design and life-cycle cost analysis with air-source variable refrigerant flow and distributed photovoltaic systems, Renew. Sustain. Energy Rev. 118 (2020). doi:10.1016/j.rser.2019.109508.

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

[37] 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.

[38] K. Voss, I. Sartori, R. Lollini, Nearly-zero, Net zero and Plus Energy Buildings – How definitions & regulations affect the solutions The, REHVA. (2012).

[39] 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.

[40] 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.

[41] 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.

[42] 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.

[43] 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.

[44] 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).

[45] 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.

[46] 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.

[47] 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.

[48] 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.

[49] 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.

[50] 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. 2019, Vol. 11, Page 4814. 11 (2019) 4814. doi:10.3390/SU11174814.

[51] 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.

[52] 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.

[53] 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.

[54] 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.

[55] 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.

[56] 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.

[57] 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.

[58] 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. 187 (2019). doi:10.1016/j.energy.2019.115916.

[59] 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.

[60] 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.

[61] 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, in: IEEE PES Innov. Smart Grid Technol. Conf. Eur., 2012. doi:10.1109/ISGTEurope.2012.6465820.

[62] 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.

[63] 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.

[64] 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.

[65] 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.

[66] 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.

[67] 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.

[68] 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.

[69] 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.

[70] 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.

[71] 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.

[72] C. Hammer, West Village Case Study: Designers and Occupants, n.d. http://www.pge.com/mybusiness/energysavingsrebates/rebatesincentives/zne pilotprogram/ (accessed February 2, 2021).

[73] 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.

[74] R. Mazza, Sustainable Design Has Changed Building Design, J. Green Build. 2 (2007) 12–17. doi:10.3992/jgb.2.3.12.

[75] A. Sev, How can the construction industry contribute to sustainable development? A conceptual framework, Sustain. Dev. 17 (2009) 161–173. doi:10.1002/sd.373.

[76] P. Thibaudeau, Integrated Design is Green, J. Green Build. 3 (2008) 78–94. doi:10.3992/jgb.3.4.78.

[77] CEC, Improving conditions for green building construction in North America: Enhancing capabilities of the green workforce, Montreal, Commission for Environmental Cooperation, 2013.

[78] L. Thomas, M. Hall, Implementing ESD in Architectural Practice – An Investigation of Effective Design Strategies and Environmental Outcomes, in: Plea2004 - 21th Conf. Passiv. Low Energy Archit. Eindhoven, Netherlands, 2004: pp. 19–22.

[79] W.G. Reed, E.B. Gordon, Integrated design and building process: what research and methodologies are needed?, Build. Res. Inf. 28 (2000) 325–337. doi:10.1080/096132100418483.

[80] N. Malin, Integrated Design, Environ. Build. News. 13 (2004).

[81] BUSBY PERKINS+WILL, STANTEC CONSULTING, ROADMAP FOR THE INTEGRATED DESIGN PROCESS, 2007. http://perkinswill.com/sites/default/files/Roadmap for the IDP.pdf.

[82] The American Institute of Architects, Integrated Project Delivery: A Guide, 2007. doi:10.1016/j.autcon.2010.09.002.

[83] CEC, Improving Green Building Construction in North America: Guide to Integrated Design and Delivery, Montreal, Canada: Commission for Environmental Cooperation., 2015.

[84] N. Larsson, The Integrated Design Process; History and Analysis, (2009). http://www.iisbe.org/node/88.

[85] A. Craig, Using integrated design to achieve net-zero, Consult. Specif. Eng. (2014).

[86] EVO, Core Cconcepts - IPMVP - International Performance Measurement and Verification Protocol, (2016).

[87] ASHRAE, ASHARE Guidelines 14 - Measurement of energy and demand savings., 8400 (2002) 1–165.

[88] M.D. Knight, Teams, contracts & BIM, ASHRAE J. 50 (2008) 72+74+76+78+80. https://www.scopus.com/inward/record.uri?eid=2-s2.0-54049120023&partnerID=40&md5=8121276eb18dbfae895205600dcdd570.

[89] M.B. Bomba, B. Parrott, Integrated project delivery and building information modeling : A new breed of contract, PCI Journal2. (2010) 146–153.

[90] T.K. Hai, A. Yusof, S. Ismail, L.F. Wei, A Conceptual Study of Key Barriers in Construction Project Coordination, J. Organ. Manag. Stud. 2012 (2012). doi:10.5171/2012.795679.

[91] P. Hoonakker, P. Carayon, T. Loushine, Barriers and benefits of quality management in the construction industry: An empirical study, Total Qual. Manag. Bus. Excell. 21 (2010) 953–969. doi:10.1080/14783363.2010.487673.

[92] W.H. Ko, S. Schiavon, G. Brager, B. Levitt, Ventilation, thermal and luminous autonomy metrics for an integrated design process, Build. Environ. 145 (2018) 153–165. doi:10.1016/j.buildenv.2018.08.038.

[93] S. Chardon, B. Brangeon, E. Bozonnet, C. Inard, Construction cost and energy performance of single family houses: From integrated design to automated optimization, Autom. Constr. 70 (2016) 1–13. doi:10.1016/j.autcon.2016.06.011.

[94] J. Kanters, M.C. Dubois, M. Wall, Architects design process in solar-integrated architecture in Sweden, Archit. Sci. Rev. 56 (2013) 141–151. doi:10.1080/00038628.2012.681031.

[95] R. Leoto, G. Lizarralde, Challenges in evaluating strategies for reducing a building's environmental impact through Integrated Design, Build. Environ. 155 (2019) 34–46. doi:10.1016/j.buildenv.2019.03.041.

[96] S. Vassigh, T. Spiegelhalter, Integrated design pedagogy for energy efficient design: Tools for teaching carbon neutral building design, in: Energy Procedia, Elsevier Ltd, 2014: pp. 2062–2069. doi:10.1016/j.egypro.2014.10.171.

[97] What is M&V - Efficiency Valuation Organization (EVO), (n.d.). https://evo-world.org/en/m-v/what-is-m-v (accessed September 21, 2020).

[98] A. Napolitano, F. Noris, R. Lollini, Measurement and Verification protocol for Net Zero Energy Buildings, IEA SHC/ECBS Task 40/Annex 52. (2013).

[99] D. Crawley, S. Pless, P. Torcellini, Getting to Net Zero, 2009. http://www.osti.gov/bridge (accessed March 18, 2020).

[100] 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.

[101] 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.

[102] 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.

[103] 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.

[104] 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.

[105] E. Burman, D. Mumovic, J. Kimpian, Towards measurement and verification of energy performance under the framework of the European directive for energy

performance of buildings, Energy. 77 (2014) 153–163. doi:10.1016/j.energy.2014.05.102.

[106] R. Gupta, M. Gregg, R. Cherian, Developing a new framework to bring consistency and flexibility in evaluating actual building performance, Int. J. Build. Pathol. Adapt. 38 (2019) 228–255. doi:10.1108/IJBPA-04-2019-0032.

[107] Y. Laaroussi, M. Bahrar, M. El Mankibi, A. Draoui, A. Si-Larbi, Occupant presence and behavior: A major issue for building energy performance simulation and assessment, Sustain. Cities Soc. 63 (2020) 102420. doi:10.1016/j.scs.2020.102420.

[108] B. Pioppi, C. Piselli, C. Crisanti, A.L. Pisello, Human-centric green building design: the energy saving potential of occupants' behaviour enhancement in the office environment, J. Build. Perform. Simul. 13 (2020) 621–644. doi:10.1080/19401493.2020.1810321.

[109] Q. Ali, M.J. Thaheem, F. Ullah, S.M.E. Sepasgozar, The Performance Gap in Energy-Efficient Office Buildings: How the Occupants Can Help?, Energies. 13 (2020) 1480. doi:10.3390/en13061480.

[110] FEMP, M&V Guidelines: Measurement and Verification for Performance-Based Contracts Version 4.0, 2015. https://energy.gov/eere/femp/downloads/mv-guidelines-measurement-and-verification-performance-based-contracts-version.

[111] 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.

[112] X. Ye, X. Xia, Optimal metering plan for measurement and verification on a lighting case study, Energy. 95 (2016) 580–592. doi:10.1016/j.energy.2015.11.077.

[113] D. Lee, C.C. Cheng, Energy savings by energy management systems: A review, Renew. Sustain. Energy Rev. 56 (2016) 760–777. doi:10.1016/j.rser.2015.11.067.

[114] R. Zmeureanu, H. Vandenbroucke, Use of trend data from BEMS for the ongoing commissioning of HVAC systems, in: Energy Procedia, Elsevier Ltd, 2015: pp. 2415–2420. doi:10.1016/j.egypro.2015.11.207.

[115] M.C. Burkhart, Y. Heo, V.M. Zavala, Measurement and verification of building systems under uncertain data: A Gaussian process modeling approach, Energy Build. 75 (2014) 189–198. doi:10.1016/j.enbuild.2014.01.048.

[116] T. Walter, P.N. Price, M.D. Sohn, Uncertainty estimation improves energy measurement and verification procedures, Appl. Energy. 130 (2014) 230–236. doi:10.1016/j.apenergy.2014.05.030.

[117] C. V. Gallagher, K. Bruton, K. Leahy, D.T.J. O'Sullivan, The suitability of machine learning to minimise uncertainty in the measurement and verification of energy savings, Energy Build. 158 (2018) 647–655. doi:10.1016/j.enbuild.2017.10.041.

[118] Y. Heo, V.M. Zavala, Gaussian process modeling for measurement and verification of building energy savings, Energy Build. 53 (2012) 7–18.

doi:10.1016/j.enbuild.2012.06.024.

[119] X. Xia, J. Zhang, Mathematical description for the measurement and verification of energy efficiency improvement, Appl. Energy. 111 (2013) 247–256. doi:10.1016/j.apenergy.2013.04.063.

[120] M.T. Ke, C.H. Yeh, C.J. Su, Cloud computing platform for real-time measurement and verification of energy performance, Appl. Energy. 188 (2017) 497–507. doi:10.1016/j.apenergy.2016.12.034.

[121] C. V. Gallagher, K. Leahy, P. O'Donovan, K. Bruton, D.T.J. O'Sullivan, IntelliMaV: A cloud computing measurement and verification 2.0 application for automated, near real-time energy savings quantification and performance deviation detection, Energy Build. 185 (2019) 26–38. doi:10.1016/j.enbuild.2018.12.034.

[122] J. Granderson, P.N. Price, D. Jump, N. Addy, M.D. Sohn, Automated measurement and verification: Performance of public domain whole-building electric baseline models, Appl. Energy. 144 (2015) 106–113. doi:10.1016/j.apenergy.2015.01.026.

[123] G.R. Newsham, Measurement and verification of energy conservation measures using whole-building electricity data from four identical office towers, Appl. Energy. 255 (2019). doi:10.1016/j.apenergy.2019.113882.

[124] M. Angelidou, Smart cities: A conjuncture of four forces, Cities. 47 (2015) 95–106. doi:10.1016/j.cities.2015.05.004.

[125] M. Jia, A. Komeily, Y. Wang, R.S. Srinivasan, Adopting Internet of Things for the development of smart buildings: A review of enabling technologies and applications, Autom. Constr. 101 (2019) 111–126. doi:10.1016/j.autcon.2019.01.023.

[126] L. Vandercruysse, C. Buts, M. Dooms, A typology of Smart City services: The case of Data Protection Impact Assessment, Cities. 104 (2020) 102731. doi:10.1016/j.cities.2020.102731.

[127] D. Kolokotsa, The role of smart grids in the building sector, Energy Build. 116 (2016) 703–708. doi:10.1016/j.enbuild.2015.12.033.

[128] Y. Su, Smart energy for smart built environment: A review for combined objectives of affordable sustainable green, Sustain. Cities Soc. 53 (2020) 101954. doi:10.1016/j.scs.2019.101954.

[129] L. Bailey, Classifying smart buildings: a guide to four levels of smart - WORKTECH Academy, (n.d.). https://www.worktechacademy.com/classifying-smart-buildings-four-levels-of-smart/ (accessed April 11, 2021).

[130] EU, DIRECTIVE 2018/844 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL, Off. J. Eur. Union. (n.d.). https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L0844&from=EN (accessed November 27, 2018).

[131] EU, Europe's Digital Decade: digital targets for 2030 | European Commission, (2021). https://ec.europa.eu/info/strategy/priorities-2019-2024/europe-fit-digital-age/europes-digital-decade-digital-targets-2030_en (accessed April 14,

2021).

[132] EU, Smart city digital ecosystem | Shaping Europe's digital future, (2021). https://digital-strategy.ec.europa.eu/en/policies/smart-city-digital-ecosystem (accessed April 14, 2021).

[133] M. De Jong, S. Joss, D. Schraven, C. Zhan, M. Weijnen, Sustainable-smart-resilient-low carbon-eco-knowledge cities; Making sense of a multitude of concepts promoting sustainable urbanization, J. Clean. Prod. 109 (2015) 25–38. doi:10.1016/j.jclepro.2015.02.004.

[134] S.E. Bibri, J. Krogstie, Smart sustainable cities of the future: An extensive interdisciplinary literature review, Sustain. Cities Soc. 31 (2017) 183–212. doi:10.1016/j.scs.2017.02.016.

[135] A. Vanolo, Is there anybody out there? The place and role of citizens in tomorrow's smart cities, Futures. 82 (2016) 26–36. doi:10.1016/j.futures.2016.05.010.

[136] M.J. Nikki Han, M.J. Kim, A critical review of the smart city in relation to citizen adoption towards sustainable smart living, Habitat Int. 108 (2021) 102312. doi:10.1016/j.habitatint.2021.102312.

[137] L. Anthopoulos, Smart utopia VS smart reality: Learning by experience from 10 smart city cases, Cities. 63 (2017) 128–148. doi:10.1016/j.cities.2016.10.005.

[138] M.S. Csukás, R.Z. Szabó, The many faces of the smart city: Differing value propositions in the activity portfolios of nine cities, Cities. 112 (2021) 103116. doi:10.1016/j.cities.2021.103116.

[139] L. Meng, E.R. Sanseverino, A. Luna, T. Dragicevic, J.C. Vasquez, J.M. Guerrero, Microgrid supervisory controllers and energy management systems: A literature review, Renew. Sustain. Energy Rev. 60 (2016) 1263–1273. doi:10.1016/j.rser.2016.03.003.

[140] X. Pan, X. Niu, X. Yang, B. Jacquet, D. Zheng, Microgrid energy management optimization using model predictive control: A case study in China, in: IFAC-PapersOnLine, Elsevier B.V., 2015: pp. 306–311. doi:10.1016/j.ifacol.2015.12.395.

[141] A. Mahmood, N. Javaid, S. Razzaq, A review of wireless communications for smart grid, Renew. Sustain. Energy Rev. 41 (2015) 248–260. doi:10.1016/j.rser.2014.08.036.

[142] D. Kolokotsa, K. Gobakis, S. Papantoniou, C. Georgatou, N. Kampelis, K. Kalaitzakis, K. Vasilakopoulou, M. Santamouris, Development of a web based energy management system for University Campuses: The CAMP-IT platform, Energy Build. 123 (2016) 119–135. doi:10.1016/j.enbuild.2016.04.038.

[143] S. Gaurav, C. Birla, A. Lamba, S. Umashankar, S. Ganesan, Energy Management of PV – Battery Based Microgrid System, Procedia Technol. 21 (2015) 103–111. doi:10.1016/j.protcy.2015.10.016.

[144] W. Shi, E.K. Lee, D. Yao, R. Huang, C.C. Chu, R. Gadh, Evaluating microgrid

management and control with an implementable energy management system, in: 2014 IEEE Int. Conf. Smart Grid Commun. SmartGridComm 2014, 2015: pp. 272–277. doi:10.1109/SmartGridComm.2014.7007658.

[145] M.M. Froufe, C.K. Chinelli, A.L.A. Guedes, A.N. Haddad, A.W.A. Hammad, C.A.P. Soares, Smart Buildings: Systems and Drivers, Buildings. 10 (2020) 153. doi:10.3390/buildings10090153.

[146] S. Wang, Making buildings smarter, grid-friendly, and responsive to smart grids, Sci. Technol. Built Environ. 22 (2016) 629–632. doi:10.1080/23744731.2016.1200888.

[147] M.H. Dadashi-Rad, A. Ghasemi-Marzbali, R.A. Ahangar, Modeling and planning of smart buildings energy in power system considering demand response, Energy. 213 (2020) 118770. doi:10.1016/j.energy.2020.118770.

[148] L. Chen, Q. Xu, Y. Yang, J. Song, Optimal energy management of smart building for peak shaving considering multi-energy flexibility measures, Energy Build. 241 (2021) 110932. doi:10.1016/j.enbuild.2021.110932.

[149] J. Al Dakheel, C. Del Pero, N. Aste, F. Leonforte, Smart buildings features and key performance indicators: A review, Sustain. Cities Soc. 61 (2020) 102328. doi:10.1016/j.scs.2020.102328.

[150] A.H. GhaffarianHoseini, N.D. Dahlan, U. Berardi, A. GhaffarianHoseini, N. Makaremi, The essence of future smart houses: From embedding ICT to adapting to sustainability principles, Renew. Sustain. Energy Rev. 24 (2013) 593–607. doi:10.1016/j.rser.2013.02.032.

[151] A.H. Buckman, M. Mayfield, S.B.M. Beck, What is a smart building?, Smart Sustain. Built Environ. 3 (2014) 92–109. doi:10.1108/SASBE-01-2014-0003.

[152] E. Taveres-Cachat, S. Grynning, J. Thomsen, S. Selkowitz, Responsive building envelope concepts in zero emission neighborhoods and smart cities - A roadmap to implementation, Build. Environ. 149 (2019) 446–457. doi:10.1016/j.buildenv.2018.12.045.

[153] W. To, L. Lai, K. Lam, A. Chung, Perceived Importance of Smart and Sustainable Building Features from the Users' Perspective, Smart Cities. 1 (2018) 163–175. doi:10.3390/smartcities1010010.

[154] W.J. Mitchell, E-topia:"Urban life, Jim-but not as we know it", MIT Press, Cambridge MA, 1999.

[155] 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.

[156] X. Ferrada, D. Núñez, A. Neyem, A. Serpell, M. Sepúlveda, A Lessons-learned System for Construction Project Management: A Preliminary Application, Procedia - Soc. Behav. Sci. 226 (2016) 302–309. doi:10.1016/j.sbspro.2016.06.192.

[157] M. Shokri-Ghasabeh, N. Chileshe, Knowledge management Barriers to capturing

lessons learned from, Constr. Innov. 14 (2014) 108–134. doi:10.1108/CI-06-2013-0026.

[158] 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.

[159] 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.

[160] 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.

[161] R. Zmeureanu, Assessment of the Energy Savings due to the Building Retrofit, 25 (1990) 95–103.

[162] 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.

[163] 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.

[164] Mathworks, Design Time Series NARX Feedback Neural Networks - MATLAB & Simulink, (n.d.). https://www.mathworks.com/help/deeplearning/ug/design-time-series-narx-feedback-neural-networks.html (accessed April 30, 2021).

[165] A.L. Pisello, C. Piselli, G. Pignatta, C. Fabiani, F. Ubertini, F. Cotana, M. Santamouris, Net Zero Energy settlements in Europe: first findings of the Zero-Plus Horizon 2020 project, (2016). doi:10.5281/ZENODO.583467.

[166] ZERO-PLUS, (2020). http://www.zeroplus.org/ (accessed May 4, 2020).

[167] 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.

[168] 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).

[169] S. Isaac, S. Shubin, G. Rabinowitz, Cost-Optimal Net Zero Energy Communities, Sustainability. 12 (2020) 2432. doi:10.3390/su12062432.

[170] ZERO-PLUS, Designing Net Zero Energy (NZE) Settlements - Tools and Methods, 2020.

[171] 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.

[172] 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, in: IOP Conf. Ser. Earth Environ. Sci., Institute of Physics Publishing, 2020: p. 012038. doi:10.1088/1755-1315/410/1/012038.

[173] B. Fladvad Nielsen, E. Resch, I. Andresen, The role of utility companies in municipal planning of smart energy communities, Int. J. Sustain. Dev. Plan. 13 (2018) 695–706. doi:10.2495/SDP-V13-N4-695-706.

[174] D.O. Aghimien, A.E. Oke, C.O. Aigbavboa, Barriers to the adoption of value management in developing countries, Eng. Constr. Archit. Manag. 25 (2018) 818–834. doi:10.1108/ECAM-04-2017-0070.

[175] A. Darko, A.P.C. Chan, E.E. Ameyaw, B.J. He, A.O. Olanipekun, Examining issues influencing green building technologies adoption: The United States green building experts' perspectives, Energy Build. 144 (2017) 320–332. doi:10.1016/j.enbuild.2017.03.060.

[176] B.G. Hwang, W.J. Ng, Project management knowledge and skills for green construction: Overcoming challenges, Int. J. Proj. Manag. 31 (2013) 272–284. doi:10.1016/j.ijproman.2012.05.004.

[177] G. Papachristos, N. Jain, E. Burman, N. Zimmermann, D. Mumovic, M. Davies, A. Edkins, Low carbon building performance in the construction industry: A multi-method approach of project management operations and building energy use applied in a UK public office building, Energy Build. 206 (2020). doi:10.1016/j.enbuild.2019.109609.

[178] N. Winston, Regeneration for sustainable communities? Barriers to implementing sustainable housing in urban areas, Sustain. Dev. 18 (2010) 319–330. doi:10.1002/sd.399.

[179] L.E. Thomas, Evaluating design strategies, performance and occupant satisfaction: A low carbon office refurbishment, Build. Res. Inf. 38 (2010) 610–624. doi:10.1080/09613218.2010.501654.

[180] Z.M. Gill, M.J. Tierney, I.M. Pegg, N. Allan, Low-energy dwellings: the contribution of behaviours to actual performance, Build. Res. Inf. 38 (2010) 491–508. doi:10.1080/09613218.2010.505371.

[181] V. Gianfrate, C. Piccardo, D. Longo, A. Giachetta, Rethinking social housing: Behavioural patterns and technological innovations, Sustain. Cities Soc. 33 (2017) 102–112. doi:10.1016/j.scs.2017.05.015.

[182] CEN, EN 16798-1:2019 - Energy performance of buildings - Ventilation for buildings - Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and aco, (2019). https://standards.cen.eu/dyn/www/f?p=204:110:0::::FSP_PROJECT,FSP_ORG_ID:41425,6138&cs=11EDD0CE838BCEF1A1EFA39A24B6C9890 (accessed October 13, 2020).

[183] CEN, EN ISO 52000-1:2017 - Energy performance of buildings - Overarching EPB assessment - Part 1: General framework and procedures, (2017). https://standards.cen.eu/dyn/www/f?p=204:110:0::::FSP_PROJECT,FSP_ORG_ID:39126,628909&cs=12B879FA9CB0107D867641BE595FCFF91 (accessed October 13, 2020).

[184] ISO, ISO 50001:2018 - Energy management systems — Requirements with guidance for use, (2018). https://www.iso.org/standard/69426.html (accessed October 13, 2020).

[185] A.B. Sharma, L. Golubchik, R. Govindan, Sensor faults: Detection methods and prevalence in real-world datasets, ACM Trans. Sens. Networks. 6 (2010) 1–39. doi:10.1145/1754414.1754419.

[186] J. Granderson, S. Touzani, S. Fernandes, C. Taylor, Application of automated measurement and verification to utility energy efficiency program data, Energy Build. 142 (2017) 191–199. doi:10.1016/j.enbuild.2017.02.040.

[187] 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.

[188] L. Richardson, S. Ruby, RESTful web services, O'Reilly, 2007.

[189] 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.

[190] 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.

[191] 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.

[192] D.M. Strong, Y.W. Lee, R.Y. Wang, Data quality in context, Commun. ACM. 40 (1997) 103–110. doi:10.1145/253769.253804.

[193] 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.

[194] NTP: The Network Time Protocol, (n.d.). http://www.ntp.org/ (accessed July 13, 2020).

[195] 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).

[196] Meteotest, Meteonorm Software, (2016). https://meteonorm.com (accessed May 21, 2020).

[197] UK Department for Communities and Local Government (DCLG), UK's national calculation method for non domestic buildings, (2004). http://www.uk-ncm.org.uk/.

[198] carbonfootprint.com - International Electricity Factors, (2020). https://www.carbonfootprint.com/international_electricity_factors.html (accessed February 28, 2021).

[199] Italy: household electricity price 2017-2018 | Statista, (n.d.). https://www.statista.com/statistics/881421/household-electricity-price-in-italy/ (accessed February 28, 2021).

[200] 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.

[201] 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.

[202] 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.

[203] 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.

[204] 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.

[205] M.Q. Raza, A. Khosravi, A review on artificial intelligence based load demand forecasting techniques for smart grid and buildings, Renew. Sustain. Energy Rev. 50 (2015) 1352–1372. doi:10.1016/j.rser.2015.04.065.

[206] E. Provata, D. Kolokotsa, S. Papantoniou, M. Pietrini, A. Giovannelli, G. Romiti, Development of optimization algorithms for the Leaf Community microgrid, Renew. Energy. 74 (2015) 782–795. doi:10.1016/j.renene.2014.08.080.

[207] S. Sepasi, E. Reihani, A.M. Howlader, L.R. Roose, M.M. Matsuura, Very short term load forecasting of a distribution system with high PV penetration, Renew. Energy. 106 (2017) 142–148. doi:10.1016/j.renene.2017.01.019.

[208] 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.

[209] S. Sharma, A. Dua, M. Singh, N. Kumar, S. Prakash, Fuzzy rough set based energy management system for self-sustainable smart city, Renew. Sustain. Energy Rev. 82 (2018) 3633–3644. doi:10.1016/j.rser.2017.10.099.

[210] M. Beccali, M. Cellura, V. Lo Brano, A. Marvuglia, Forecasting daily urban electric load profiles using artificial neural networks, Energy Convers. Manag. 45 (2004) 2879–2900. doi:10.1016/j.enconman.2004.01.006.

[211] M.Q. Raza, M. Nadarajah, D.Q. Hung, Z. Baharudin, An intelligent hybrid short-term load forecasting model for smart power grids, Sustain. Cities Soc. 31 (2017) 264–275. doi:10.1016/j.scs.2016.12.006.

[212] S. Chapaloglou, A. Nesiadis, P. Iliadis, K. Atsonios, N. Nikolopoulos, P. Grammelis, C. Yiakopoulos, I. Antoniadis, E. Kakaras, Smart energy management algorithm for load smoothing and peak shaving based on load forecasting of an island's power system, Appl. Energy. 238 (2019) 627–642. doi:10.1016/j.apenergy.2019.01.102.

[213] The Mathworks Inc., MATLAB - MathWorks, Www.Mathworks.Com/Products/Matlab. (2016). doi:2016-11-26.

[214] A. Mellit, A.M. Pavan, A 24-h forecast of solar irradiance using artificial neural network: Application for performance prediction of a grid-connected PV plant at Trieste, Italy, Sol. Energy. 84 (2010) 807–821. doi:10.1016/j.solener.2010.02.006.

[215] A. Giaconia, F. Montagnino, F. Paredes, F. Donato, G. Caputo, D. Mazzei, Co-generation and innovative heat storage systems in small-medium CSP plants for distributed energy production, AIP Conf. Proc. (2017). doi:10.1063/1.4984476.

[216] G. Notton, M.L. Nivet, C. Voyant, C. Paoli, C. Darras, F. Motte, A. Fouilloy, Intermittent and stochastic character of renewable energy sources: Consequences, cost of intermittence and benefit of forecasting, Renew. Sustain. Energy Rev. 87 (2018) 96–105. doi:10.1016/j.rser.2018.02.007.

[217] A. Mavrigiannaki, N. Kampelis, D. Kolokotsa, D. Marchegiani, L. Standardi, D. Isidori, C. Christalli, Development and testing of a micro-grid excess power production forecasting algorithms, Energy Procedia. 134 (2017) 654–663. doi:10.1016/j.egypro.2017.09.583.

[218] R.K. Jain, K.M. Smith, P.J. Culligan, J.E. Taylor, Forecasting energy consumption of multi-family residential buildings using support vector regression: Investigating the impact of temporal and spatial monitoring granularity on performance accuracy, Appl. Energy. 123 (2014) 168–178. doi:10.1016/j.apenergy.2014.02.057.

Annex I – Measurement specifications and monitoring timeline

Table 23: Measurement specifications

No	Measurement name	Units	Range	Resolution	Accuracy (±)
1	Space temperature	°C	0 -40	0.1	0.5°C
2	Space relative humidity	%	10-90	1	10.00%
3	Space CO2 level	ppm	0-2000	20	40 ppm
4	Space occupancy	0/1	0-1		
5	Space Illumination	Lux	0-500	0.2	0.5lux
6	Window open/close	On/Off	0-1	-	-
7	Door open/close	On/Off	0-1	-	-
8	Space Setpoint temperature	°C	0 -40	0.1	0.5°C
9	Building HVAC electric power	W	0-25000	0.1	0.10%
10	Building HVAC electric consumption	Wh	0 -99,999,999 MWh	1	0.1Wh
11	Building electric power (consumption)	W	0-25000	0.1	0.10%
12	Building electric energy consumption	Wh	0 -99,999,999 MWh	1	0.1Wh
13	Building Domestic hot water	Wh	0 -99,999,999 MWh	1	0.1Wh
14	Building PV electric power	W	0-25000	0.1	0.10%
15	Building PV electric energy production	Wh	0 -99,999,999 MWh	1	0.1Wh
16	Building Battery Stored Energy	Wh	0 -99,999,999 MWh	1	0.1Wh
17	Outdoor air temperature	°C	-40 - 64	0.1	1
18	Relative humidity	%	1-100	1	4.00%
19	Wind Speed	m/s	1-50	0.4	5.00%
20	Wind direction	deg	0 – 360	1	3deg
21	Rain	mm	0 -950	0.2	5.00%
22	Global radiation	W/m²	0-2000	50	10.00%

Table 24: Monitoring timeline and duration

Actions	Type	Duration	Comments
Pre-occupancy checks	In field U-value measurement (external walls)	1/2/2019-5/3/2019; more than 1 month	In both R1 and R2, the U-value for external walls is slightly higher than that one declared at the design stage

Actions	**Type**	**Duration**	**Comments**
Pre-occupancy checks	Air permeability (blower door test)	5/3/2019; 1 day	R2 was not completed (including all finishes) when the test was performed, thus the results for this building cannot be considered reliable
Pre-occupancy checks	Thermal imaging	5/3/2019; 1 day	In both R1 and R2, the infrared analysis on the external facades show a non-homogeneous surface temperature distribution
Pre-occupancy monitoring	Indoor microclimate monitoring in one room (air temperature and relative humidity, mean radiant temperature, air speed, radiant asymmetry, CO_2 concentration, VOCs), only air temperature and relative humidity monitoring in a second room, outdoor air temperature and relative humidity monitoring	R1: 18/6/2018-6/7/2018; about 3 weeks R2: 1/2/2019-5/3/2019; more than 1 month	The pre-occupancy monitoring in R1 was shorter than 1 month due to construction delays and the need of owners to move in

Actions	Type	Duration	Comments
Post-Occupancy monitoring	Space air temperature and relative humidity, CO_2 concentration, occupancy presence, illuminance, window and door opening/closing, building equipment and HVAC electricity consumption, PVs electricity production	starting from 09/06/2019 to 15/08/2020 (1st year data used for the evaluation; 09/06/2019 to 08/06/2020)	All sensors for IEQ were connected to the WebGIS platform in June 2019, but there was a delay with the data transmission due to the Rotex G1 connection problems.
Weather station	Outdoor air temperature and relative humidity, wind speed and direction, rain, pressure, global solar radiation	starting from 07/05/2019 to 15/8/2020 (1st year data used for the evaluation; 09/06/2019 to 08/06/2020)	Installed on the rooftop of R2

ANNEX II – Collected data quality: Uniqueness and Completeness

Double entries (uniqueness) were minimal and after being identified they were removed from the dataset (Table 25). The results of completeness are discussed in detail in the following paragraphs.

Table 25: Double entries in the collected data.

Time series	Double entries
R1 dataset	4 double entries, 0.02%
R2 dataset	6 double entries, 0.03%
Weather dataset	8 double entries, 0.04%

Two cases of missing data occurred during the studied period: (i) lost entries due to system communication disruption and (ii) empty entries that were entered as -100.

Table 26: Missing data from Residence 1 (R1) monitoring.

R1 Indoor data (9/6/19 – 7/2/20)					
Recorded (percentage of expected)		**Empty entries** (percentage of recorded)	**Total missed** (empty + lost)		
97.38%		0.01%	2.63%		
Total missed per type:	**CO2**	**Temperature**	**RH**	**Illuminance**	**Presence**
	2.62%	2.63%	2.62%	2.62%	2.66%
R1 Consumption data (9/6/19 – 7/2/20)					
Recorded (percentage of expected)		**Empty entries** (percentage of recorded)	**Total missed** (empty + lost)		
97.38%		0%	2.62%		
Total missed per type:	**HVAC**		**Appliances**		
	2.62%		2.62%		
R1 PV Production data (one year)					
Recorded (percentage of expected)		**Empty entries** (percentage of recorded)	**Total missed** (empty + lost)		
100%		3.43%	3.43%		

Overall, the percentage of missing consumption and IEQ data for R1 during the period 9/6/19-7/2/20 is low and mainly occurred due to lost entries that were not recorded on the platform, owing to system communication disruption (Table 26). When looking at R2 (Table 27), for which one-year data have been collected and assessed, the percentage of missing data is higher. In this case too, missing data occurred due to entries that were not recorded on the platform.

Table 27: Missing data from Residence 2 (R2) monitoring.

R2 Indoor data (one year)		
Recorded (percentage of expected)	**Empty entries** (percentage of recorded)	**Total missed** (empty + lost)

81.14%	0.03%	18.89%			
Total missed per type:	**CO2**	**Temperature**	**RH**	**Illuminance**	**Presence**
	18.88%	18.88%	18.88%	18.87%	18.93%
R2 Consumption data (one year)					
Recorded (percentage of expected)	**Empty entries** (percentage of recorded)	**Total missed** (empty + lost)			
81.14%	0.011%	18.87%			
Total missed per type:	**HVAC**	**Appliances**			
	18.87%	18.87%			
R2 PV Production data (one year)					
Recorded (percentage of expected)	**Empty entries** (percentage of recorded)	**Total missed** (empty + lost)			
100%	8.39%	8.39%			

In February 2020, data transfer from the houses to the platform was interrupted due to an unsuccessful update of the routers. The outbreak of COVID-19 and the subsequent restrictions prohibited technical assistance to reach the settlement. As a result, transmission of monitored consumption and IEQ data from Residence 1 to the platform stopped for approximately 6 months. Nevertheless, monitoring of consumption data is cumulative and imputation of the missing period was possible as soon as the communication was restored. In R2, the occupants being more confident with technology have been able to reset communication, although not able to fix the problem. This fact is visualized in Figure 48. Until February 2020, occurrences of missing data have been recorded, which have been tackled by experts. However, after February, communication in R1 could not be restored and in R2, it took longer time for communication to be restored by building occupants, resulting in longer periods of missing data.

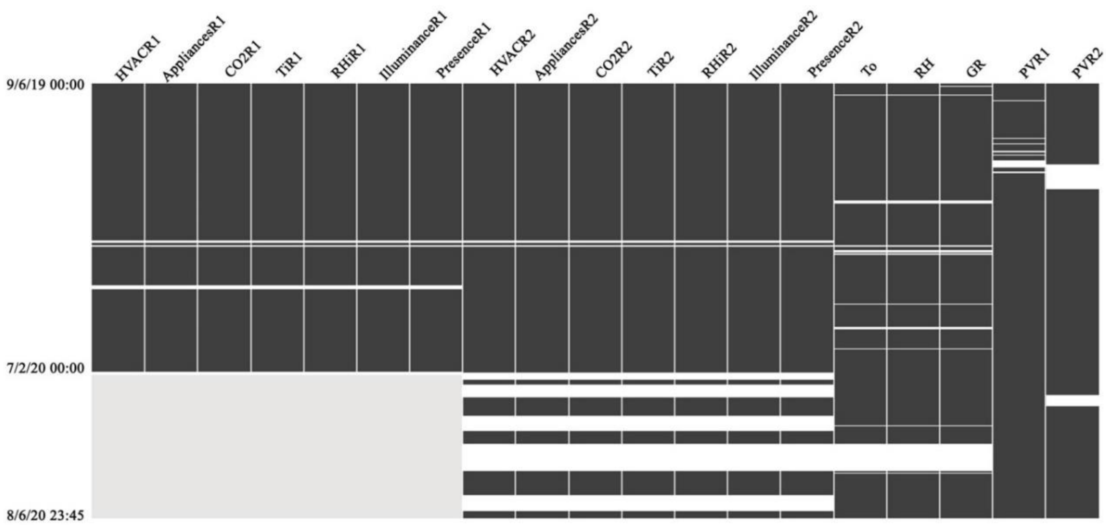


Figure 48: Missing data pattern for: Residence1 (HVACR1, AppliancesR1, CO2R1, TiR1-indoor air temperature R1, RHiR1-indoor relative humidity R1, IlluminaceR1, PresenceR1), Residence2 (HVACR2, AppliancesR2, CO2R2, TiR2-indoor air temperature R2, RHiR2-indoor relative humidity R2, IlluminaceR2, PresenceR2), the Weather Station (To-outside air temperature, RH-relative humidity, GR-global radiation), and the PV installations (PVR1-PV on R1, PVR2-PV on R2).

Table 28: Missing data from Weather Station

Weather data (one year)			
Recorded (percentage of expected) 90.80%		**Empty entries** (percentage of recorded) 0.23%	**Total missed** (empty + lost) 9.41%
Total missed per type:	**Temperature**	**RH**	**Global Radiation**
	9.37%	9.37%	9.47%

The weather station (Table 28) communicates directly with the platform and the PV production data (Table 26 and Table 27) are gathered and transferred to the Web-GIS through a third party platform (the inverter's manufacturer platform). The different routes of communication that have been designed and implemented between the monitoring equipment and the platform effectively shape the missing data pattern (Figure 48). As a result, missing data have occurred in different periods for the houses, for the weather station, and for the PVs. Observing the missing data pattern from the beginning of monitoring, simultaneous periods that both houses have missing data are observed; this is due to miscommunication of the KNX router with the Web-GIS platform. In periods that both houses and the weather station have missing data, this is due to lost internet connectivity or power disruption.