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Measurement and Verification of Zero Energy Settlements: Lessons Learned from Four Pilot Cases in Europe

Angeliki Mavrigiannaki [1,*], Kostas Gobakis [1], Dionysia Kolokotsa [1], Kostas Kalaitzakis [2], Anna Laura Pisello [3], Cristina Piselli [3], Rajat Gupta [4], Matt Gregg [4], Marina Laskari [5], Maria Saliari [5], Margarita-Niki Assimakopoulos [5] and Afroditi Synnefa [6]

1 School of Environmental Engineering, Technical University of Crete, 74100 Chania, Greece; kgobakis@isc.tuc.gr (K.G.); dkolokotsa@enveng.tuc.gr (D.K.)
2 School of Electrical and Computer Engineering, Technical University of Crete, 74100 Chania, Greece; kkalaitzakis@isc.tuc.gr
3 Department of Engineering, University of Perugia, 06121 Perugia, Italy; anna.pisello@unipg.it (A.L.P.); cristina.piselli@unipg.it (C.P.)
4 Low Carbon Building Research Group, Oxford Institute for Sustainable Development, Oxford Brookes University, Oxford OX3 0BP, UK; rgupta@brookes.ac.uk (R.G.); mgregg@brookes.ac.uk (M.G.)
5 Group of Building Environmental Studies, Physics Department, National and Kapodistrian University of Athens, 10679 Athens, Greece; mlaskari@phys.uoa.gr (M.L.); msaliari@phys.uoa.gr (M.S.); masim@phys.uoa.gr (M.-N.A.)
6 Faculty of Built Environment, University of New South Wales (UNSW), Sydney 2052, Australia; asynnefa@phys.uoa.gr
* Correspondence: amavrigiannaki@isc.tuc.gr

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Abstract: Measurement and verification (M&V) has become necessary for ensuring intended design performance. Currently, M&V procedures and calculation methods exist for the assessment of Energy Conservation Measures (ECM) for existing buildings, with a focus on reliable baseline model creation and savings estimation, as well as for reducing the computation time, uncertainties, and M&V costs. There is limited application of rigorous M&V procedures in the design, delivery and operation of low/zero energy dwellings and settlements. In the present paper, M&V for four pilot net-zero energy settlements has been designed and implemented. The M&V has been planned, incorporating 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. Under this scope, M&V is an integrated, iterative process that is accompanied by quality control in every step. Quality control is a significant component of the M&V, and the proposed quality control procedures can support the preparation and implementation of automated M&V. The proposed framework can be useful to project managers for integrating M&V into the project management and development process and explicitly aligning it with the rest of the design and construction procedures.

Keywords: measurement and verification; monitoring; performance evaluation; ZERO-PLUS

1. Introduction

In the highly energy-performing and efficient built environment, measurement, and verification (M&V) of performance is a crucial task. Implementation of M&V is a prerequisite within the European

Union's Energy Efficiency Directive [1]. Continuous monitoring and verification of performance is also emphasized in an amendment of the Energy Performance of Buildings Directive (EPBD) [2]. International green building standards (e.g., LEED–Leadership in Energy and Environmental Design), prescribe a series of basic (prerequisite) and advanced (extra credits) steps towards M&V, intending to set up a feedback mechanism on building energy use trends, performance assessment, and consequent measures for improved efficiency [3]. The introduction of the Integrated Design Process (IDP) as a new approach to building design, which is especially suited for designing high performance, sustainable buildings, further supports energy performance measurement and verification. A critical step of the IDP that greatly differentiates it from the conventional design process is building monitoring after construction during the in-use phase [4–6].

1.1. Why Measure and Verify?

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 [7]. M&V is particularly vital in performance-based contracts, where a third party contractor guarantees the performance of the implemented energy-saving measures and the installed equipment [8]. However, the feedback obtained from M&V, apart from allowing the evaluation of the adopted energy efficiency measures, benefits multiple aspects related to the design and operation of buildings.

The deviation between design and actual building performance, known as the performance gap, has been well established in the literature [9–11], and is a strong driver for performing M&V [12]. Through measuring and analyzing actual performance, data can be fed back into simulation models allowing the quantification and evaluation of the performance gap [9], as well as the identification of causes and consequent mitigating actions [10,11], such as lack of precision in the definition of realistic boundary conditions at building and settlement level [13]. The measured performance also provides feedback to occupants, thus assisting the transition of occupant behavior to an energy-conscious mindset and enhancing the success of the applied energy strategies and further assisting in closing the performance gap [14]. In particular, performance monitoring can be exploited to develop real-time and feedforward information strategies to drive more rational energy-related occupant behavior [15,16].

The feedback provided through M&V feeds decisions for building energy management aiming to improve performance [17], as well as Demand Side Management (DSM) programs aiming to optimize costs and efficiency [18]. Measured performance data are the cornerstone of Building Energy Management Systems (BEMS) and have long been utilized for energy performance management [19,20]. Besides, BEMS is the developing of smart capabilities to adapt to the rise of a smart built environment [19]. Energy monitoring is becoming essential for the transition from traditional energy distribution grids to smart grids, thus BEMS becomes part of a more comprehensive energy management system, where energy flows are regulated and optimized with the application of suitably designed controls [21]. To adapt to these technological advances, a new form of M&V, named M&V 2.0, is under development. M&V 2.0 is automated and offers continuous, near real-time feedback on savings [22].

1.2. M&V Protocols

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. M&V requires planning and the coordination of various actions, a complicated process to begin with, but supported through well-established protocols—the more prominent being the International Measurement and Verification Protocol (IPMVP) [23] and the ASHRAE Guideline 14 [24].

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 [23]. 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 [24].

Given the zero-energy building (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 [25].

1.3. M&V State of the Art

Research to date has been focused on ECM implemented on existing buildings and investigating methods for reducing uncertainty in the baseline performance, as well as automating the M&V.

Heo and Zavala proposed Gaussian Process (GP) models for reducing the uncertainty of the baseline. The proposed modeling approach was implemented in two office building case studies and demonstrated that the GP models could reduce baseline uncertainty by also capturing non-linear and complex data, as well as reducing the time and costs of M&V [26]. On the same path, Burkhart et al. proposed a Monte Carlo expectation maximization (MCEM) framework for constructing baseline GP models. This approach could further reduce uncertainty compared to standard GP models and also could perform with less data, therefore reducing the M&V costs [27].

Walter et al. have worked with linear regression models and cross-validation algorithms to estimate the baseline and the uncertainty of the baseline models. The effectiveness of their method was tested in 17 commercial buildings. The authors concluded that, apart from being effective, the simple regression model studied is easy to use, making it attractive to apply [28]. Gallagher et al. tested various machine learning algorithms and concluded that machine learning is suitable for reducing uncertainty when considering M&V in industrial buildings. In this specific case, the artificial neural network algorithm had the best performance [29].

Granderson et al. presented a statistical methodology for assessing the baseline predicted energy. The methodology was tested on a large sample of 389 buildings, using five different baseline prediction models to provide an overview of the models' performance. The authors suggested that their methodology is also applicable to automated M&V [30].

Automation of the M&V, namely M&V 2.0, is the research focus investigating the development and potential of M&V 2.0. A Cloud computing platform for the measurement and verification of energy performance in real-time was presented by Ke et al. [31]. 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 [22].

Newsham has presented a regression-based approach for M&V using whole-building data. Although not accurate for a broad span of buildings, the author concluded that this approach can be adopted in automated M&V 2.0. Furthermore, the model had similar performance between monthly and hourly data, allowing a reduced cost from hourly data [32].

Xia and Zhang have approached the formulation of the optimal M&V plan as a mathematical problem, where M&V cost and uncertainty are included as constraints in the problem [33]. The optimal metering plan for M&V of a lighting retrofitted project has also been solved as a mathematical problem by Ye and Xia. The objective of the problem was the optimization of M&V costs under defined M&V accuracy constraints [18].

1.4. Motivation

Established protocols exist which list standard M&V procedures and calculation methods for the assessment of ECM on existing buildings. These protocols have been created with the initial purpose of providing a basis for the evaluation of energy-saving programs. Therefore, M&V in literature has been linked mainly to ECM implemented on existing, primarily industrial, or office buildings. From that point of view, interest has been focused on developing methodologies for the creation of a reliable baseline model and savings estimation, as well as for reducing the computation time, uncertainties, and M&V costs.

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 proposed 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 [12]. 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 settlement level of analysis.

For new-built projects in the era of net ZEB, 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 was also confirmed by the approach of Gupta et al. [12]. Therefore, the present paper zooms out from the specifics of energy-saving estimation methodologies and uncertainties to look at the broader M&V context and how this can be placed within new-built project management and as part of a project's design, construction and operation. This research paper offers a novel structured, integrated proposal for designing and implementing M&V in an advanced type of buildings, i.e., new high-performance buildings as part of a net-zero energy settlement.

M&V for Net-Zero Energy Settlements

Specifically, the present paper describes the newly developed M&V framework that was followed for the M&V of pilot net-zero energy settlements in Europe. Although the M&V protocol for single net-zero energy buildings is available, a settlement is, indeed, an entity more complicated than a single building. A settlement is composed of more than one building of similar or various different uses, where energy is communally produced, stored, and managed. When considering a settlement 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 paper aims not to provide a new protocol but rather a novel framework for incorporating and implementing the guidance provided in established protocols. Therefore, this comprehensive M&V framework for settlements is 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 project management and development process and specifically aligning it with the rest of the design and construction procedures.

2. Methodology

The methodology followed for the development of the M&V framework presented in this paper is depicted in Figure 1. 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 pilot settlements, 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.

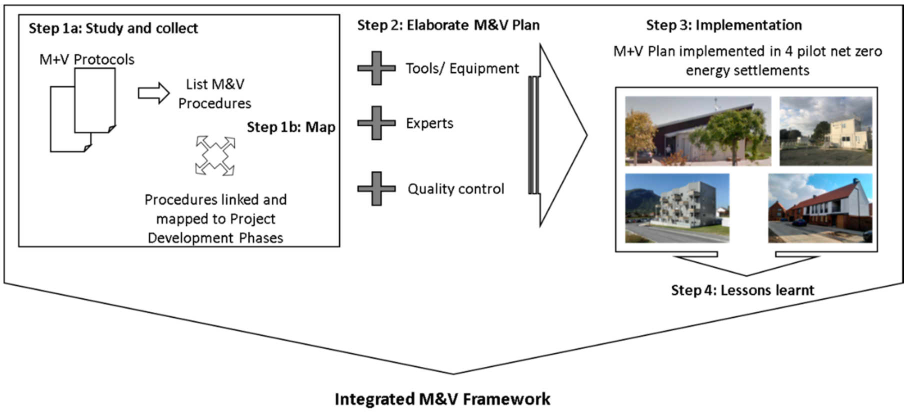

Figure 1. Schematic representation of the measurement and verification (M&V) methodology.

2.1. Pilot Settlements

The Measurement and Verification Plan, which is the basis for the present work, was developed to serve the measurement and verification of four pilot net-zero energy settlements designed and constructed under the Horizon 2020 project ZERO-PLUS [34,35]. Each settlement comprises residential buildings, energy production technologies, and energy conservation technologies (Table 1). The four pilot settlements are composed of varying building sizes and types, including villas in Italy, detached and semi-detached dwellings in the U.K., a social housing building block in France, and a prefabricated container system in Cyprus. The settlements are designed to produce at least 50 kWh/m^2/year renewable energy, while each residential unit's net regulated energy use (the sum of heating, cooling, ventilation and auxiliary energy use minus the renewable energy) is less than 20 kWh/m^2/year. A net-zero energy settlement's investment cost is reduced by 16% compared to single net-zero energy buildings through the customization and modularity available at the settlement level.

M&V is imperative for the verification of the settlements' energy-related targets and the IEQ of the buildings. For monitoring purposes, a monitoring schema was created that records data from the buildings and the technologies. The collected data are logged on a Web-GIS platform. The Web-GIS platform is the core of the monitoring schema, where data are stored and analyzed for performance assessment and prediction (Figure 2). [36].

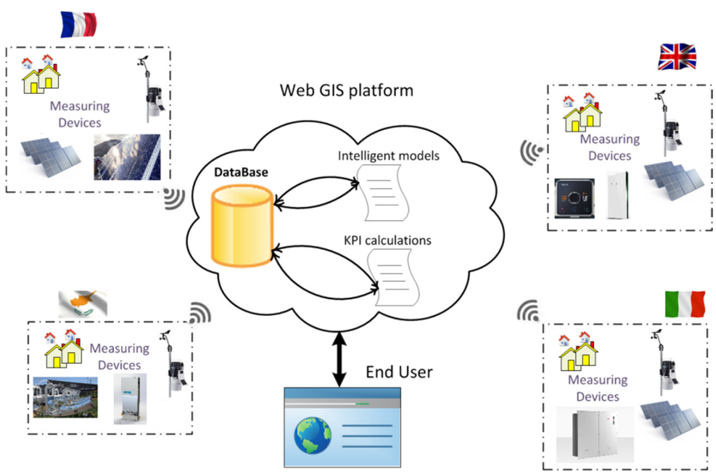

Figure 2. Overall Web-GIS platform layout for monitoring of the four pilot settlements (adapted from [36]).

Table 1. Summary of the pilot settlements' characteristics.

Location	Buildings		Technologies		
	Type	Size	Energy Conservation	Energy Generation	Energy Management
Italy	2 villas	241–259 m^2	Composite cool thermal insulation	Rooftop PV	- Storage and inverter system - Load control - BEMS system
UK	1 detached, 2 semi-detached	101–156 m^2	Typical insulation	Rooftop PV	- Batteries for the management of electricity demand from PV and off-peak reduced rate charging - BEMS system with a learning thermostat
France	Social housing apartment block	18 apartments, 4 floors, 1277 m^2	Typical insulation	- Rooftop PV - Hybrid electrical and thermal solar panels on the roof - Connection to biomass district heating network	- Thermal energy stored in hot water tank - Energy regulation (low temperature at night)
Cyprus	Prefabricated container system	130–390 m^2	- Composite cool thermal insulation - Solar air conditioning system	Combined heat and power generation system	-

2.2. *M&V Planning*

Planning the M&V of a project is a complex process that involves the coordination of various actions. As already discussed, M&V protocols exist—IPMVP [23], ASHRAE Guideline 14 [24], Measurement and Verification Protocol for Net Zero Energy Buildings [25]—that outline the 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 [37], EN ISO 52000-1:2017 for the definition of the energy performance of buildings [38], ISO 50001:2018 for monitoring the energy management at settlement level [39].

Link Activities to Phases

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:

- Pre-design
- Design
- Construction
- Post-construction/Pre-occupancy
- Post-occupancy

Additionally, 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)

Finally, a mapping of the procedures and the project development phases was produced (Table 2). This mapping forms the basis for further development of M&V planning.

Table 2. 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 Innovative Technologies</th><th>Building Monitoring</th><th>Social Science Surveys</th></tr>
<tr><td>1st phase
Pre-Design</td><td colspan="4">Selection of expert partners
Goal setting</td></tr>
<tr><td>2nd phase
Design</td><td colspan="3">Energy boundaries
Data to be monitored
Monitoring technology
Quality control</td><td rowspan="3"></td></tr>
<tr><td>3rd phase
Construction</td><td colspan="3">Proper installation and function
Commissioning</td></tr>
<tr><td>4th phase
Post-construction
—Pre-occupancy</td><td>Commissioning procedures</td><td colspan="2">Pre-occupancy monitoring
Commissioning</td></tr>
<tr><td rowspan="2">5th phase
Post-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>

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.

2.3. Lessons Learned

The present paper is built on experience from implementation and specifically from the design and construction of four zero energy settlements. Apart from reporting the M&V plan created, it is useful also to identify what worked well, whether difficulties occurred and the reasons, and what the involvement was from the various experts in each phase.

The lessons learned were captured through a series of questions that were answered by the project partners. Three sets of questions were prepared for the three main groups: (a) Case study owners, (b) Case study support teams, and (c) Technology providers. Furthermore, lessons learned were obtained through remarks raised in meeting discussions.

'Lesson learned' sessions are an opportunity to identify success stories, pitfalls, and/or unintended outcomes (positive or negative) and recognize things that went well, something that might be done differently, the causes of pitfalls, and suggestions for facing or avoiding those [40]. Furthermore, lessons learned sessions contribute to knowledge management and establishing institutional knowledge [40,41].

3. M&V Framework

Figure 3 is a graphic representation of the M&V framework as it was designed and implemented in the four pilot settlements. It depicts the 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. Continuous feedback and iteration between the phases are necessary.

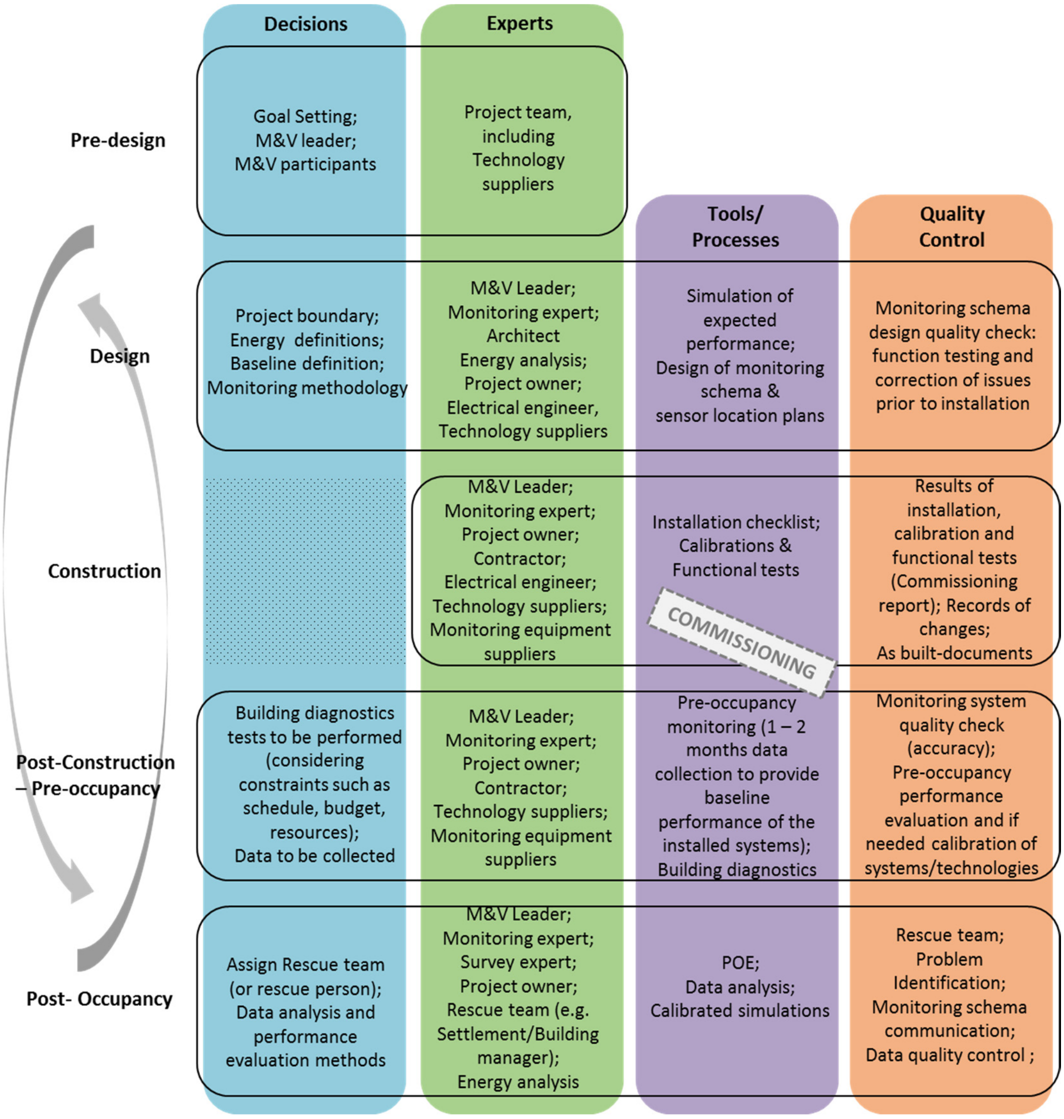

Figure 3. Graphic representation of the M&V framework that has been developed and implemented in the four pilot settlements.

3.1. Pre-Design

The pre-design is the phase that establishes the targets of the project. The Key Performance Indicators (KPIs) that are subject to measurement and verification in a settlement project can be defined for the whole settlement as well as for individual buildings or building types within the settlement, or systems of the settlement. Verification 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 leader), energy analysis expert, survey expert).

3.2. Design

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

At this phase, the monitoring methodology is designed, including the monitoring equipment that should 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. The decisions and designs of this phase are updated and reevaluated along with the design development.

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 settlements. Possible deficiencies that might be identified need to be 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.

3.3. Construction/Installation

The third phase comprises the measurement and verification procedures to be followed during the construction of the settlements 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. As in the previous phase, it is expected that any changes made during construction/installation are recorded and as-built documents are prepared.

3.3.1. Installation of Technologies

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.

3.3.2. Monitoring Equipment Installation

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.

3.4. Post-Construction—Pre-Occupancy

Post-construction—pre-occupancy measurement and verification procedures include commissioning after constructing the settlements 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 settlement's 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. In case that pre-occupancy monitoring is not feasible, alternative options need to be considered early on.

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.

3.4.1. 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.

3.4.2. 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 needs to be tested as well.

3.4.3. Monitoring System Testing

At this phase, the monitoring system of the settlement 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.

3.5. Post-Occupancy

During post-occupancy, the settlement'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 KPIs. 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 post-construction monitoring responsibilities, evaluation of measurements and results, and troubleshooting (e.g., lost data). Quality control is a significant aspect of this phase.

3.5.1. Rescue Team

A rescue team (or person) 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 settlement manager or settlement maintenance service.

3.5.2. Data Quality Control

During this phase, continuous fault detection of the monitoring equipment is implemented. The acceptable limits of the monitoring equipment's accuracy have been decided among the technical specifications for monitoring in the design phase. The selected commercial products to be installed should comply with these requirements. Additionally, 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 the following reasons: sensor failure, power disruption, or errors in data transfer. In case of any failure, an appointed person of the rescue team needs to be notified of faults, verify the faults, and take corrective actions in collaboration with the monitoring coordinator. Subsequently, appropriate procedures for cleaning and imputing missing data are set in place. Data quality control ensures the collection of a high-quality dataset, thus building trust in the obtained results.

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

1. Assessment of measurement errors: a robust and straightforward rule-based method fault detection algorithm based on [42] is implemented 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 concerning the measuring resolution
3. Implementation of data imputation procedures based on the amount and pattern of missing data

3.5.3. Problem Identification

The net-zero energy settlements are entities with high performance expectations composed of multiple components that contribute to the expected performance. Measurement and verification results might reveal poor performance, therefore it is critical to identify the cause. In case that the measured performance of the settlement is not as expected, a problem identification procedure can assist the identification of the possible cause, whether it is due to faulty installation of the technologies, incorrect settings, or possibly a combination of reasons.

The problem identification procedure is a protocol of steps that are suggested to be followed and implemented if performance is not as expected for a defined period (e.g., one month). The first step searches for exogenous causes of unexpected performance (i.e., extreme weather). The subsequent steps try to identify poor fabric performance, poor technology performance, occupants' interactions with the buildings and systems, and finally, possible false data.

4. Discussion

4.1. Integrated Framework

An M&V framework to assess the field performance of zero energy settlements was implemented. The M&V activities designed and implemented were recorded in an M&V Plan, continuously evolving along with the project development and updated as needed. In that sense, the M&V was developed with an integrated design approach. The IDP is an iterative design process that requires various professionals' involvement from the start of a project. The IDP works in feedback loops between the project development phases and, in contrast to the conventional design process, includes the project's operational phase to monitor, measure, and verify the in-use performance [4,5]. Planning the measurement and verification of a new-built project is a complex process integral to IDP, and the approach that was followed demonstrates how the M&V design and implementation are related to each of the IDP steps, although it is intended to serve as the last step of the process (Figure 4).

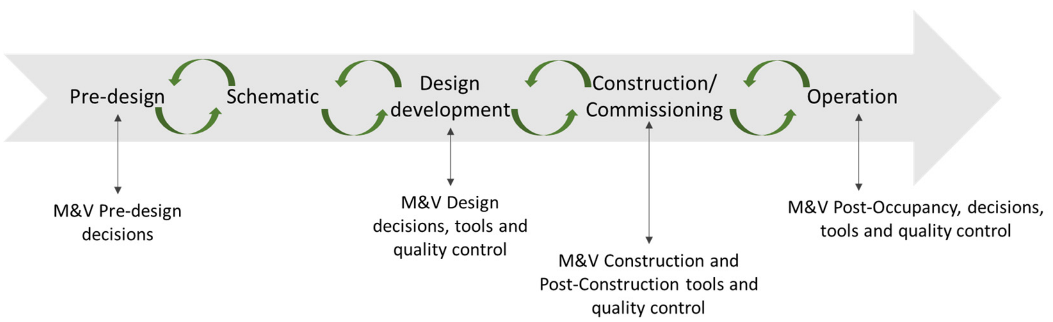

Figure 4. M&V development concerning the integrated design process (IDP). The representation of the IDP is a result of guidance provided in [4–6].

Indeed, experience from the implementation on four pilot settlements revealed that the design of the M&V is closely related to a project's design development and optimization. The pilot partners identified that critical decisions for the M&V are made during the early design stages. During these stages, 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.

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 [23,24]. Specifically, the net-ZEB balance evaluation is determined by the selected energy boundary [25]. The measurement and verification of a net-ZEB settlement becomes a more complex task requiring informed planning decisions from the early design stages. The energy balance boundary includes energy flows within a micro-grid, in which case automated M&V becomes imperative for monitoring and regulating energy towards the improvement of the net-ZEB performance.

Furthermore, in a new development, the initial design intentions are subject to evaluation. For a settlement, 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 [23,24]. Informed planning is still crucial for selecting the metrics to be measured and the measuring approach (including equipment) to provide the necessary calibration data.

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 should be prepared. Furthermore, the electrical drawings need to include the monitoring installation. This design phase planning assists the construction and installation phases, and it is highlighted through the lessons learned as a practice to be adopted in future projects. Planning of the M&V activities for 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.

4.2. Quality Control

Quality control is a significant task within the M&V planning and implementation, and an important subject of quality control has been the development and operation of the monitoring schema with a Web-GIS platform in its core. The monitoring schema measures and collects parameters related to IEQ, building and settlement energy consumption, building and settlement energy production, energy storage (if implemented), and weather data. On the platform, the data are collected, analyzed, and visualized for immediate performance feedback.

Implementation of intelligent models for prediction of performance can further support energy management. In light of the M&V 2.0, the M&V planning and quality control procedures discussed in this paper 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 [22,43]. 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 settlements' performance with multiple data sources.

Post-occupancy quality control has provided invaluable feedback regarding cases of lost communication and missing data (Table 3). In the pilot settlements, missing data occurrences were recorded due to system communication disruptions and sensor malfunction. Sensor malfunction was related to the faulty reading of the measurements. Communication disruption was 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 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.

Table 3. 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%

4.3. Involved Experts

The proposed framework presupposes close collaboration among the partners throughout the process. This type of collaboration is inherent to the IDP and is expected for the design and construction of net-zero energy settlements [44].

An M&V coordinator's work in collaboration with a rescue team or a rescue person was proven necessary to achieve timely identification and mitigation of monitoring malfunctions. Such collaboration is recognized as invaluable through the lessons learned.

4.4. Occupant Interactions

In planning the M&V for a settlement project, the involvement of occupants becomes a critical parameter of the M&V planning decisions. Future owners or occupants need to be included in the process and informed about the location of monitoring equipment in their houses and settlements, to avoid possible objections at a later stage that could cause unexpected changes or delays, as was the case in one of the pilot settlements.

In the pilots, non-technical user guides, called "Welcome Packages," were also prepared and handed to the occupants. These documents contained basic information about the technologies and the monitoring equipment installed on the residences and the settlements, guidance on accessing the Web-GIS platform, and contact details of the rescue team.

Finally, considering occupants' involvement, the monitoring planning was ruled by the necessary provisions of the General Data Protection Regulation (GDPR).

5. Conclusions

The M&V is integral to the design and operation of a high-performing built-environment. In the present paper, a novel comprehensive M&V framework developed and implemented in four zero energy settlements has been presented.

The guidance provided in well-established M&V protocols has been deployed and adjusted to the design of M&V for the net-zero energy settlement boundary, while the lessons learned from its design and implementation have been incorporated in the final proposed M&V framework. Having been tested through implementation, the proposed M&V framework can be used as guidance for similar future new-built settlement projects.

The proposed M&V framework is an integrated, iterative approach whose foundation is set from the project initiation. Many experts in close collaboration are involved along the process, and quality control is a significant component of the process, especially concerning the design and implementation of the monitoring schema that supports the M&V.

The applicability of the presented M&V framework is not necessarily limited to settlements. In fact, the proposed framework can be introduced to the project management of new-built projects along with the IDP implementation. Finally, the proposed quality control procedures can be relevant to the design of a fully automated M&V, namely M&V 2.0. Recognizing the limitations, it is expected that the proposed M&V framework can be subject to cost, time, and/or human resources constraints.

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Abbreviations

BEMS	Building Energy Management System
DSM	Demand Side Management
ECM	Energy Conservation Measure
EPBD	Energy Performance of Buildings Directive
GDPR	General Data Protection Regulation
GP	Gaussian Process
IDP	Integrated Design Process
IEQ	Indoor Environmental Quality
IPMVP	International Measurement and Verification Protocol
KPIs	Key Performance Indicators
MCEM	Monte Carlo expectation maximization
M&V	Measurement and Verification
POE	Post Occupancy Evaluation
ZEB	Zero Energy Building

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