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Development of a quality assurance tool to minimize performance gap in nZEBs

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The purpose of this study was to develop a quality assurance tool applicable to the construction phase of nearly zero energy office building projects. The EPBD recast directive of 2010 set in motion the European Union's transition into the construction of nearly Zero Energy Buildings (nZEBs) by December 31, 2018 for all new buildings owned by public authorities and December 31, 2020 for all new buildings. In the near future, the minimum value of total energy use or *E-value* for office buildings in Finland will be reduced from 170 (current national building code) to 90 kWh/m^2 per year. This is predicted to result in an energy performance gap.

The scope of this study was to examine both previous literature in the field of nZEBs, energy performance measurement metrics, and quality assurance during the construction phase of nZEBs, as well as determine if there is a relationship between the quality assurance principles of passive house buildings and nZEB office buildings. This study employed two research methodologies, a literature review and case studies of nZEB office buildings to attempt to find solutions to minimize performance gap in nZEB office building projects through quality assurance methods.

This study found that there is a significant performance gap between calculated annual energy consumption and the actual measured annual energy consumption of office buildings in use. Furthermore, this study found that there are several similarities in the quality assurance of nZEB and passive house office building projects. These quality assurance principles from the Passive House standard certification process may be transferred to nZEB office building projects as one solution to lower this performance gap.

Keywords	Quality assurance, nZEB office buildings, energy efficiency

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Tämän työn tarkoituksena oli kehittää laadunvarmistustyökalu sovellettavaksi lähes nollaenergiatoimisto (nZEB) -rakennushankkeiden rakennusvaiheeseen. Vuoden 2010 EPBD recast -direktiivi käynnisti EU:n siirtymisen lähes nollaenergiarakentamiseen. Tämä direktiivi määräsi, että 31. joulukuuta 2018 mennessä uusien julkisessa omistuksessa olevien rakennusten ja 31. joulukuuta 2020 kaikkien muiden rakennusten tulee olla lähes nollaenergiarakennuksia. On arvioitu, että pian Suomessa asetettavissa uusissa rakennusmääräyksissä minimimäärä kokonaisenergian kulutukselle (E-luku) tulee laskemaan 170 kWh/m^2:stä per vuosi (nykyinen rakennusmääräys SRMK 2012) 90 kWh/m^2:iin per vuosi. Tämän uskotaan aiheuttavan eroja rakennusten energiatehokkuuksien välillä.

Tämä työ rajattiin lähes nollaenergiarakentamiseen (nZEB) toimistojen osalta, energiatehokkuusmittareihin ja laadunvarmistukseen nZEB-hankkeiden rakennusvaiheissa. Lisäksi tarkoituksena oli selvittää, onko passiivirakennusten ja nZEB toimistorakentamisen laadunvarmistusperiaatteiden välillä yhteyttä. Tässä työssä käytettiin hyödyksi alan kirjallisuutta sekä tapaustutkimuksia nZEB-toimistohankkeista, jotta löydettäisiin ratkaisuja mahdollisten energiatehokkuuserojen minimoimiseksi.

Tämä työ esittää energiatehokkuuseron lasketun vuotuisen kulutusenergian ja todellisen mitatun vuotuisen kulutusenergian käytön toimistorakennusten käyttövaiheiden välillä. Sen lisäksi tämä työ löysi yhtenäisyyksiä nZEB ja passiivitalo -toimistorakennusten laadunvarmistusperiaatteiden välillä. Tämän tutkimuksen tärkein johtopäätös oli se, että hyödyntämällä passiivitalojen laadunvarmistusperiaatteita nZEB toimistorakennus -hankkeisiin, arvioitua energiatehokkuuseroa voitaisiin pienentää.

Avainsanat	Laadunvarmistus, nZEB toimitilat, energiatehokkuus

Contents

Appendices

List of Acronyms

ASHRAE – American Society of Heating, Refrigerating, and Air-Conditioning Engineers
BAS – Building Automation System
BMS – Building Management System
BPIE – Buildings Performance Institute Europe
CCTC – Concrete Core Temperature Control
CDD – Cooling Degree Days
DGNB – German Society for Sustainable Building
DHW – Domestic Hot Water
EC – European Commission
EED – Energy Efficiency Directive
EEM – Energy Efficient Measures
EERB – Energy Efficiency Ratio for Buildings
EPC – Energy Performance Certificate
EPoB – Energy Performance of Buildings
EPBD – Energy Performance of Buildings Directive 2010 of the European commission
EPC – Energy Performance Certificate
FInZEB – Finnish nearly Zero Energy Building project funded by the Ministry of the Environment of Finland
GHG – Greenhouse Gas
HDD – Heating Degree Days
HVAC – Heating Ventilating Air-Conditioning system
IEA – International Energy Agency
LCC – Life Cycle Costing
LEB – Low Energy Building
LEED – Leadership in Energy and Environmental Design
LMGII – Load Matching and Grid Interaction Indicators
MVHR – Mechanical Ventilation with Heat Recovery
NGO – Non Government Organization
nZEB – Nearly Zero Energy Building
PCM – Phase Change Materials
PHI – Passive House Institute
PHPP – Passive House Planning Package design tool
PI – Performance Indicator
PV – Photovoltaic
RER – Renewable Energy Ratio
RES – Renewable Energy Sources
SPF – Specific Fan Power
SRMK – Suomen Rakentamismääräyskokelma (The national building code of Finland)
TRY – Test Reference Year
ZEB – Zero Energy Building

Definitions

Air infiltration rate (q50) – A measure of the average volume of air leakage across a specific surface area of building envelope structure per hour with 50 Pa pressure difference applied [$m^3/m^2/h$].[1]

Air leakage – Uncontrolled air movement through the building envelope caused by pressure differences across a building assembly or –element such as an external wall caused by wind, stack effect and imbalance of the HVAC system [1 air-exchange/ hour].[2]

Air tightness (n50) – A measure of the uncontrolled air movement resistance of the building envelope expressed in air exchange rate at a specific-, intentionally produced pressure (e.g.50Pa).[1]

Building commissioning – A quality assurance process for enhancing the delivery of a project. The process upon verifying and documenting that the facility inclusive of all systems and assemblies are planned, designed, installed, tested operated and maintained to fulfil the client's quality requirements usually with the guidance of a commissioning consultant.[3]

Building envelope – The complete working unit of a building's assemblies and -elements which shield the conditioned interior space from the exterior natural environment and govern the rate at which hygrothermal properties are transferred between such.[1]

Coefficient of performance (COP) – The ratio of the rate of heat delivered to the rate of energy input, for a system operating at design conditions.[1]

Design energy consumption – The predicted energy demand of a building annually.[1]

Delivered energy – Energy expressed inclusive of primary energy factors for energy carriers, supplied to the building across the system boundary to meet a share (1-100%) of the building energy demands. Delivered energy can also be referred to as "site energy" or "purchased energy".[4]

Energy Efficiency Ratio for Buildings (EERB) – The ratio of energy required to energy used or ER/EU.[1]

Energy performance of a building – The measured or calculated amount of energy which a building actually used or estimated for its standard operation including: energy use for heating, cooling, ventilation, DHW, lighting and appliances.[5]

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[1] Mahdavi, A. An introduction to building physics. Vienna, Austria: International Resources Group (IRG) and the Vienna University of Technology; 2010.

[2] ISO 16818:2008 (E) Building environment design – Energy efficiency – Terminology. Geneva, Switzerland: ISO; 2008.

[3] ASHRAE. ASHRAE Guideline 0-2005: The Commissioning Process; 4 Definitions. Atlanta, Georgia, USA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.; 2005.

[4] EN 15603:2008. Energy performance of buildings. Overall energy use and definition of energy ratings. Brussels, Belgium: CEN; 2008.

[5] EN 15316-1:2007. Heating Systems In Buildings - Method For Calculation Of System Energy Requirements And System Efficiencies. General. Brussels, Belgium: CEN; 2007.

E-value – The weighted total energy use of a building determined by the ratio of the predicted annual net energy imports multiplied by the primary energy factors for energy carriers all divided by the net heated floor area of the building.[6]

Exergy – Property of a system that describes its work potential. It is the measure of a system's potential maximum useful work available to cause change as it reaches equilibrium with its environment in Joules. [J]. [1]

Exfiltration – Air leakage in the outward direction through the building envelope. It is the uncontrolled air movement through cracks and orifices in the exterior wall assemblies, around fenestrations, external doors and any other building elements of the building envelope.[7]

Exported energy – Energy expressed inclusive of primary energy factors for energy carriers, delivered away from the building across the system boundary to be used outside the system boundary. [4]

Fenestration – Any building assembly in the roof or walls of a building which allows light to transfer through it. Fenestrations include all related structures including: framing (mullions, muntins and dividers), internal-, external- and integral shading structures.[1]

Floor area, gross – The total conditioned floor area (heated or cooled) for an entire building, which excludes cellars or other unheated spaces.[1]

Heat flux density (q) – The rate at which thermal energy is transferred through a surface across one square meter of the surface [W/m^2].[8]

Heating, Ventilating, Air-Conditioning system (HVAC) – The collective term for the systems that provide ventilation, condition air, purify air, heat spaces, cool spaces and control indoor air quality of a building or portion of a building.[1]

Heat recovery ventilation annual efficiency rate – The amount of thermal energy that a ventilation system's heat recovery unit (HRU) exchanges between extract air and supply air per year [%].

Heat transfer – The transfer of thermal energy by one of three mechanisms or a combination of: thermal conduction, thermal convection or thermal radiation.[9]

Hygrothermal properties –Building physical properties which express both humidity and temperature[8]

Infiltration – Air leakage in the inward direction through the building envelope. It is the uncontrolled air movement through cracks and orifices in the external wall assemblies, around fenestrations, external doors and any other building elements of the building envelope.[1]

Integrated building design – A design process in which the whole design team (architects, engineers and other consultants) works in synergy to develop the building project design in a several iterative revisions from the conceptual design to final detailed design.[10]

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[6] The Ministry of the Environment of Finland. Building energy efficiency (Rakennusten energiatehokkuus: Määräykset ja ohjeet 2012) D3 Suomen rakentamismääräyskokoelma 2012. Helsinki, Finland; 2011.

[7] ISO 16818:2008 (E) Building environment design – Energy efficiency – Terminology. Geneva, Switzerland: ISO; 2008.

[8] Wit, M. H. Heat, Air and Moisture in Building Envelopes. Eindhoven, Germany: Technische Universiteit Eindhoven; 2008.

[9] ISO. ISO 9251:1987 (en) Thermal insulation — Heat transfer conditions and properties of materials — Vocabulary. Geneva, Switzerland: ISO; 1987.

[10] Heiselberg, P., editor. IEA ECBCS Annex 44: Integrating Environmentally Responsive Elements in Buildings: Expert Guide – Part I Responsive Building Concepts. Hertfordshire, UK: AECOM Ltd.; 2009.

Life cycle cost –The total cost of an asset over its life cycle including initial costs, operation and maintenance costs (O&M costs) and the residual value of the asset at the end of its useful life minus any disposal costs.[11]

Life Cycle Costing (LCC) – An economic methodology whose main principle is to determine the most cost-effective asset or design over a time frame examined. The life cycle costs of an asset is an assets net sum of costs of over its life cycle including initial costs, operation and maintenance costs (O&M costs) and the residual value of the asset at the end of its useful life minus any disposal costs.[12]

Nearly Zero Energy Building (nZEB) – A building that has a very high energy performance. Additionally, nZEB require energy to a significant extent from renewable sources (renewable sources produced on-site or nearby) to supply the nearly zero or very low amount of energy demand of the building.[12]

Net delivered energy – The difference of delivered - and exported energy, calculated inclusive of primary energy factors for energy carriers.[13]

Net Zero Energy Building (NZEB) – A building which the net energy consumed over a year is offset by an equal amount of energy produced on site.[14]

Passive house – A building which is designed to provide good indoor air quality and thermal comfort solely from heating or cooling of the supply air, without recirculated make-up air.[15]

Overarching primary energy – Shift towards an energy system where renewable energy is dominant and fossil systems exist only at seldom events such as peak loads.[16]

Performance Indicator (PI) – Measurable quantitative performance indicators for the designed indoor environmental conditions specified at design- or occupancy phase. These performance indicators are a measure of how a building performs in energy efficiency, greenhouse gas emissions and cost. For example, the energy demand of the building envelope is measured in kWh and energy demand per floor unit in kWh/m2. Also, primary (weighted) energy performance is calculated as previously, but multiplied by the used energy carrier's given weighted primary coefficient.[1]

Plus energy building – A building which the net energy consumed over a year is less than the energy produced within the building's system boundary.[14]

Primary energy – Energy that may be from non-renewable resources (resource energy), from renewable energy resources (renewable energy) or a combination of both, but has not undergone any conversion or transformation process which is used to produce energy delivered to the building. For buildings this is calculated by the energy required to produce the energy delivered to the building multiplied by the energy carrier's weighted primary energy factor.[1]

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[11] Sesana, M., M. and Salvalai, G. Overview on life cycle methodologies and economic feasibility for nZEBs. Building and Environment, 2013,67: 211-216.

[12] Council of the European Union. Council Directive 2010/31/EU of 19 May 2010 on the energy performance of buildings. Official Journal of the European Union, 2010; 53:13–35.

[13] EN 15603:2008. Energy performance of buildings. Overall energy use and definition of energy ratings. Brussels, Belgium: CEN; 2008

[14] Kagerer, F.,and Herkel, S. editors. IEA SHC task 37: Advanced Housing with Solar and Con servation: Glossary. Freiburg, Germany: Fraunhofter ISE; 2011.

[15] Feist,W. Passipedia: The Passive house resource. 2014. URL: http://passipedia.org/

[16] Atanasiu, B., Project coordinator. Principles for nearly zero-energy buildings [online]. Brussels, Belgium: Buildings Performance Institute Europe (BPIE); 2011.
URL: http://www.bpie.eu/documents/BPIE/publications/LR_nZEB%20study.pdf.

Renewable Energy Ratio (RER) – An expression of the ratio of energy produced from renewable energy sources considering total primary energy consumption of a building.[17]

Responsive building concept – An integrated design solution which takes a comprehensive design approach integrating both responsive building elements and energy-systems together. Its aim is to optimize the environmental performance of a building including: energy performance, resource consumption, indoor air quality as well as impact on the environment.[18]

Responsive building elements – A building element that adapts its functionality to internal or external changes and to occupant intervention in order to maintain an appropriate balance of the BMS. These building elements may include: advanced integrated facades, thermal mass activation, earth coupling, phase change materials and dynamic insulation.[19]

System boundary – A boundary that limits within it all the areas of the building where energy is generated or consumed.[13]

Thermal bridge – Or cold bridge, occurs when the local density of heat flow rate of a particular entity within the building envelope is significantly larger than at one or more adjacent entities. When indoor air temperature of a building is greater than outdoor air temperature a larger heat flow rate exists and creates a local cooler surface at the thermal bridge. [20 and 8]

Thermal conductivity (λ) – The measure of a material's ability to conduct heat. It measures the rate of thermal energy loss through one meter of the material thickness. [W/(m·K)] [8]

Thermal mass – Opaque structures or materials with high heat capacity and significant surface areas of the building capable of affecting building loads by passively releasing stored thermal energy as the interior and/or exterior temperature and radiant conditions fluctuate.[7]

Thermal transmittance (U) – Is the rate at which thermal energy is transferred through a surface across one square meter of the surface when both sides of the surface have combined radiant and air temperatures that differ by at least 1 degree kelvin (1°C). [W/(m^2 ·K)] [8]

Thermal resistance (R) – The rate at which object or material resists the transfer of thermal energy through a surface across one square meter of the surface with a resistance of at least 1 degree kelvin (1°C). [(m^2·K)/W] [8]

U-value ($U_{composite}$) – Also called composite thermal conductance, the overall thermal transmittance measuring the rate at which thermal energy is transferred through a building element such as a wall or complete building assembly [W/(m^2 ·K)]. It is the summation of all combined thermal resistances of all the elements in a construction, including surfaces, air spaces, and the effects of any thermal bridges, air gaps and fixings.[1 and 2]

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[17] EN 15603:2008. Energy performance of buildings. Overall energy use and definition of energy ratings. Brussels, Belgium: CEN; 2008

[18] Heiselberg, P., editor. IEA ECBCS Annex 44: Integrating Environmentally Responsive Elements in Buildings: Expert Guide – Part I Responsive Building Concepts. Hertfordshire, UK: AECOM Ltd.; 2009.

[19] Heiselberg, P., editor. IEA ECBCS Annex 44: Integrating Environmentally Responsive Elements in Buildings: Project Summary Report. Hertfordshire, UK: AECOM Ltd.; 2012.

[20] Barry, R. The Construction of Buildings. Vol.2, 5th Ed. Oxford, UK: Blackwell Science Ltd.; 1999.

1 Introduction

The built environment has a deep, far-reaching impact on the natural environment. In 2014, energy use in buildings accounted for 40 percent of energy use and 36 percent of greenhouse gas emissions of all sectors combined in the European Union [1]. To achieve the European Union's climate and energy objectives, the EU parliament has set the 2020 targets aimed at lowering the environmental impact of buildings. The 2020 targets are to reduce EU greenhouse gas (GHG) emissions by 20%, reduce primary energy consumption by 20% by improving energy efficiency and increase the share of renewable energy by 20% compared to 1990 levels [2]. Hence, steps taken to lower the environmental impact of the built environment are a significant step forward to reduce climate change and our dependence on fossil fuels. Furthermore, increasing the share of sustainable buildings also incites positive economic effects creating jobs in the building industry as well as in rapidly developing markets such as clean tech.

Furthering the progression of these objectives, the EU parliament has enacted two building energy performance directives: the EU Energy Performance of Buildings Directive (EPBD) in 2002 and then later the EPBD recast in 2010. The main goals of the EPBD recast directive are to implement an EU-wide systematic reduction of energy consumption and greenhouse gas emissions of the building sector while strengthening the legislation of the preceding EPBD directive. Effectively, this calls for national energy efficiency plans and other legislation regarding the energy performance of buildings to become ever more stringent and comparable EU-wide. Article 9 of this directive states the requirements for EU member states to transition into nearly Zero Energy Building (nZEB) construction for all newly constructed public authority owned buildings by December 31, 2018 and December 31, 2020 for all other new buildings. Furthermore, member states shall draft national plans to increase the number of nZEBs. [3]

The recently completed FInZEB-project was launched by the Finnish Ministry of the Environment to find the cost optimal metrics for nearly Zero Energy Buildings (nZEB) in Finland. The FInZEB project group has published primary energy use target values for nZEBs by building type. For office buildings the project group suggests that the minimum total energy use or *E-value* of the building should be reduced from the current national building code (SRMK D3/2012) value of 170 to 90 kWh/m^2 per year. In effect, office buildings will have the greatest reduction in E-values from current building code values, experiencing a 47% reduction [4].

The main purpose of this study is to develop a quality assurance tool applicable to the construction phase of nZEB office building projects in Finland. A secondary purpose of this study is to first investigate the presence of an energy performance gap in building energy use. This study predicts that a performance gap between calculated annual energy consumption and actual measured energy consumption of nZEB office buildings exists. If this study successfully validates this performance gap, its extent in new- construction-nZEB office buildings in Finland will then be discussed.

The scope of this study is to examine previous literature in the field of nZEBs, energy performance measurement metrics, and quality assurance during the construction phase of nZEBs. This study will focus on the theme of on-site, quality assurance procedures with the greatest potential to lower both heat losses and energy demand of buildings. These procedures will target lowering energy demand of heating, ventilating, and air-conditioning, systems (HVAC) and heat losses through both the building envelope and ventilation system in nZEB office building projects.

The goal of this study is demonstrate that the more rigorous quality assurance process and design principles required in passive house building projects are very beneficial in nZEB building projects. The more detail-orientated quality assurance process required in passive house projects will be adapted in this study to develop a quality assurance tool for the construction phase of nZEB office building projects. The development of this quality assurance tool will be a process first analysing theory, then applying this theory to a comprehensive quality assurance tool and lastly employing critical reflective learning and other learning theories to gain feedback on ways of improvement.

2 Research questions and methodology

This chapter discusses the research questions posed in this study and the overall process to find solutions to these questions. First, the research questions of this study will be presented. Second, the working plan to find solutions to these research questions is presented. Third, the research methodologies employed in this study are presented.

Fourth, the development process of the quality assurance tool created will be discusses, followed by its planned feedback.

2.1 Research questions

This study aims at finding solutions to three research questions.

Main question:

1. Is there a performance gap between design performance targets and actual measured performance of nearly zero energy office buildings in Finland?

Secondary questions:

1. If and to what extent can quality assurance and design principles from passive house buildings be applied to nZEB office building projects to minimize this performance gap?

2. Is the level of quality assurance in high energy performance buildings (such as nZEB office buildings) currently as high as it could be?

2.2 Workflow

The workflow of this study is a two phase process. Phase one of the process is to complete a comprehensive literature review and also examine two case studies of nZEB office buildings. Phase two is to review the information gathered and create a quality assurance tool. Then, feedback on the usefulness of the quality assurance tool will be collected.

The first phase of this study begins by performing a comprehensive literature review of nZEBs and low energy buildings overall with an emphasis on quality assurance in the construction phase of office buildings. After this two case studies are examined to demonstrate some successful results of nZEB office building projects internationally.

The second phase of this study consists of reviewing the information gathered and creating a quality assurance tool to minimize performance gap in nZEB office buildings in the construction phase. After that, feedback of the quality assurance tool will be sought for ways of improvement. It is hypothesized that upon completing the two research methodologies stated below it will be possible to answer the research questions of this study.

2.3 Research methodologies

First, this study aims to complete a comprehensive literature review of nZEB with emphasis on quality assurance in the construction phase of office buildings. The academic impact factor and quality of sources cited in the theory section will be of the highest degree. To gather a satisfactory representation on the current state of nZEB, published and online information resources will be reviewed for definitions, principles and energy balance. Then, theory of passive house buildings and the quality assurance of these buildings will be presented. Then, quality and quality assurance principles in building projects will be presented.

Second, this study aims to demonstrate the successful results of two nZEB office building projects internationally. Two case studies of exemplary office building projects will be reviewed to gain insight in to the state-of-the-art best practices of high energy performance construction and nZEB related principles. The information gathered from these two research methodologies will then be complied to create a quality assurance tool.

2.4 Development of a quality assurance tool for an nZEB office building

The purpose of this study is to develop a quality assurance tool applicable to the construction phase of nZEB office building projects. The development process of this quality assurance tool will start by analysing theory in nearly zero energy building- and passive house building energy efficient design with an emphasis on quality assurance in the construction phase of office buildings. After that, this theory will be applied to create a quality assurance tool. The quality assurance tool consists of a quality assurance tool package.

The quality assurance tool package is made up of a combination of a quality assurance matrix and a set of construction checklists specialized for nZEB office buildings. It is predicted that the use of this quality assurance tool will aid in minimizing the energy performance gap between design performance targets and actual measured performance of nZEB office buildings.

2.5 Feedback

The process of receiving feedback of the usefulness of the quality assurance tool is very important. Ovando found that giving and receiving feedback is a critical part of the learning process [5]. To learn effectively one must receive feedback to find out what areas one excelled in and what areas one could improve. Moreover, feedback allows one to draw connections from theory and hypothesize what results will occur when the new idea or process is implemented.

The usefulness of the quality assurance tool would be best evaluated in practical use. Gauging the usefulness of the tool in practice would consist of an in-field tests ideally in nZEB office building projects or even low energy buildings since there are few nZEB office buildings in Finland. The second part of the in-field tests would consists of post-test interviews test participants on the usefulness of the tool. However beneficial the implementation of in-field trials would be, it is not possible due to two reasons. First, there is not enough time to implement and analyse in-field test. Second, there are currently not many nZEB office building projects in Finland to study. Consequently, feedback would be needed on the usefulness of the quality assurance tool is needed. Therefore, it is planned to interview individuals involved in the low energy building projects in Finland and show them the quality assurance tool.

3 Energy efficiency of buildings policies

There is not one standardized definition for low energy buildings or energy-efficient building. In fact, just about every EU country has created their own definition. In a recent literature review Thomson and Wittchen show that each EU country has a definition of energy-efficient building adapted for their building practices and climate- as well as different scopes for energy-efficient building [6].

In a review of low energy buildings, Ng and Akasah found that researchers in previous studies all broadly define a low energy building as a building which includes energy-efficient design strategies in order to lower its energy consumption [7]. Now with the transition into creating nearly Zero Energy Buildings (nZEBs) fast approaching the European parliament has taken the lack of clear nZEB principles head on and set legislation to create a common EU-wide framework of the nZEB definition.

3.1 European Union

To make it easier for EU member states to discuss low energy buildings, the European Commission has created a common definition. The Commission defines low energy buildings as buildings that typically use high levels of insulation, energy efficient windows, good air tightness of the building envelope and heat recovery ventilation to lower heating and cooling energy demands. Low energy buildings may also include passive solar design strategies or active solar technologies. [8]

The European Council has passed two main directives aimed at reducing the energy consumption of buildings: the Energy Performance of Buildings Directive (EPBD) and the Energy Efficiency Directive (2002 and 2012 respectively). The EPBD directs EU member states on increasing the energy efficiency of the building stock. Similarly the second directive greatly influencing the building industry is the Energy Efficiency Directive (EED). The EED has several goals, but those specific to the building industry are aimed at energy efficiency in building renovation.

The EPBD has five main principles summarized in table 1 below. These five principles are primary energy performance evaluation, HVAC performance evaluation, nZEB requirements, minimum energy performance requirements for buildings and requirements to improve national plans on energy efficiency.

Table 1. The five principles of the Energy Performance of Buildings Directive [9]

Energy Performance of Buildings (EPBD) Directive	
Principle:	Required action plans for member states:
1. Primary energy performance evaluation	Energy performance certificates must be a requirement for sale or rental of buildings
2. HVAC performance evaluation	Inspection schemes must be created for heating, ventilation and air-conditioning systems (HVAC)
3. nZEB requirements	All new buildings must be nearly zero energy buildings by 2020 (public buildings by 2018)
4. Minimum energy performance requirements for buildings	Minimum energy performance requirements required for new buildings, major renovations and replacement of building elements (HVAC, roofs, walls)
5. National plans to improve energy efficiency	Financial measures must be created to improve energy efficiency of buildings

The second influential directive, the EED has three main topics. First, EU member states must undertake energy efficient renovations on at least 3 per cent of government owned buildings. Second, EU governments must only purchase energy efficient buildings. Third, member states must draft long-term national renovation strategies. [10] To further clarify the principles of the 2002 EPBD directive the European Council created a subsequent “recast” EPBD” in 2010. In the next section the EPBD recast directive will be discussed.

3.2 EPBD recast directive

Goals of the EPBD recast directive

The EPBD recast describes the highly-technical concept of nearly Zero Energy Buildings (nZEBs) as revolving around three main principles energy demand, renewable energy share and primary energy and CO_2 emissions [3]. For these three main principles to be in any way useful, several technical aspects must be defined individually by each EU member state. First, the system boundary of energy flows must be able to describe the building’s primary energy demand clearly [3]. Additionally, a threshold value of maximum energy demand of nZEB buildings must be determined. Second, the system boundary of energy flows must be specified to include renewable energy production on-site or nearby [3]. Also, the minimum share of energy from renewable energy sources must be defined. This ratio of renewable energy to total energy consumption is described by the Renewable Energy Ratio (RER) of a building. Calculation methodologies of RER are presented later in section 6.6. Third, the system boundary of energy flows must be agreed to include overarching primary energy demand and CO_2 emissions [11]. The concept of overarching primary energy refers to the imminent paradigm shift towards a new energy system where renewable energy becomes the dominant source of primary energy and fossil fuel sources are employed only at seldom events such as peak loads [12].

Definition of nZEB

The Council determined that an EU wide definition of a nZEB could not be possible, mostly because of climatic variations and differences for construction cost-optimal levels between member states. In Finland there are currently no nZEBs, because at the moment of publication of this work Finland has not yet enacted new legislation on nZEB including technical aspects such as primary energy demand. With this in mind, article two of the EPBD recast gives a broad definition of nZEBs:

> *"a (nZEB is a) building that has a very high energy performance. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby"* [3].

The first requirement of the EPBD recast is for EU member states to draft their own national legislation on the detailed principles of energy demand in nZEBs. The EPBD recast states only general design requirements of nearly Zero Energy Buildings. It could be argued that at present, the Finnish building code drives all newly constructed buildings to be buildings that have *a* **very good energy performance**. This is point developed in more detail in section 4.1.1. Article two of the 2002 EPBD previously defined energy performance of a building (EPoB) as the calculated amount of energy which a building requires for typical use including energy for heating, cooling, ventilation, domestic hot water (DHW) and lighting [9]. However, this definition was amended later in 2007 by the standard organization CEN to also include energy used for appliances [13]. As previously stated, on page 7 the metrics of energy performance of buildings, most importantly the energy balance must be determined by each member state.

In contrast to the more straightforward approach of the first requirement of the EPBD recast, the second requirement of the EPBD recast defining the share of total energy demand originating from renewable energy resources is a greater challenge [14]. Currently, neither Finnish national legislation nor the Finnish building code provide requirements for the share of energy production that must come from renewable energy resources. As the EPBD recast requires that member states draft plans to increase the amount of nZEBs, each member state must find a percentage equivalent to a **great extent** of renewable energy which is feasible nationally. Several EU member states are interpreting the phrase *of a great extent* to be equivalent to a 50%-90% allotment of total energy consumption of a building to originate from renewable energy resources in order to be consistent with EU energy and climate targets [15].

The third requirement of the EPBD recast, directs EU member states to define the energy system boundaries for **on-site or nearby** renewable energy generation. As in the other clauses of the EPBD, it is left up to the member states to determine what the energy boundaries are for *on-site* and *nearby*. On a side note, the Council gives a reason why the principles of cost optimality and nZEB energy performance are divided topics. The Council is a nonbiased third-party aside from private energy providers; so therefore, the directives it passes must not favour one type of (renewable) energy over another. In the near future, after 2020, the minimum energy performance requirements for new buildings are predicted to reach cost optimal levels [16]. This means that as precise definitions of nZEB are formed nationally, investment costs of nZEB projects are predicted to decrease in relation to the proportional increase in lifetime building energy savings as cost optimality of nZEB construction and building energy savings merge for a cost effective smooth transition.

3.3 National level

Low energy buildings

The national building code of Finland describes the requirements for and regulations on building energy efficiency and heat losses in sections C4 Insulation guidelines 2012, D3 Energy performance of buildings: Requirements and guidelines 2012, and D5 Calculation of energy use and heating demand of buildings: guidelines 2012 [17]. An overview of the definitions of low energy buildings in Finland is given in table 2 below. For more information on how low energy buildings are classified see section 4.3.

Table 2. Definitions of low energy buildings in Finland [17]

Definitions of low energy buildings			
Type of building	Provider of definition	Space heating demand [$kWh/(m^2 \cdot a^{-1})$]	Primary energy consumption [$kWh/(m^2 \cdot a^{-1})$]
Low Energy Building	National building code (D3 2012)	60 for buildings in Southern Finland 90 for buildings Northern Finland	No value given yet
Passive Energy Building	Teknologian tutkimuskeskus VTT Oy (VTT)	20-30	135-140
Passive Energy Building	Suomen Rakennus Insinöörien Liitto Ry (RIL)	20-30	75-85

Section D3 of the national building code of Finland (SRMK D3/2012) defines a generally low energy building as a building whose calculated heat losses must not exceed 85% of the heat loss calculated according to reference values for the given building type in the national building code [17]. Also, the space heating demand of low energy buildings must be 50% lower than the space heating calculated according to the building code values of a model reference building of the same building type. A second type of low energy building, a passive building is defined by VTT (a NGO) to have space heating demand between 20-30 kWh/m^2 per year and primary energy consumption between 135-140 kWh/m^2 per year for new buildings (depending on climate zone). In comparison, RIL (a NGO) defines passive energy by building type. They define a passive energy building to have space heating demand also between 20-30 kWh/m^2 per year and primary energy consumption between 75-85 kWh/m^2 per year. [17]

Nearly Zero Energy Buildings

To successfully meet the requirements of the EPBD recast, the Finnish Ministry of the Environment has created several pieces of supportive legislation and launched productive national programs and pilot studies to study nZEBs. One of the most notable studies being conducted, the FInZEB-project published its results February 2015 at the FInZEB-2015 results seminar. The FInZEB-project, was funded by the Finnish Ministry of Environment and it gathered the top experts in the sustainability and energy efficiency field. The FInZEB project is still ongoing, but its goal is to recommend Finland's nZEB requirements so that they are ambitious and cost effective, fulfil the EPBD directive, ensure the safety of structures, and ensure good indoor air quality [4]. The FInZEB project suggests the target levels of primary energy use of nZEBs by building category. For nZEB office buildings the work group suggests that total energy use or E-value of the building should be reduced from the current national building code (SRMK D3/2012) value of 170 to 90 kWh/m^2 per year [4]. The E-value is the standard performance indicator (PI) used to describe a building's calculated annual net primary energy consumption per net floor area [17].

There are factors which dictate how easily nearly Zero Energy Buildings become adopted as the norm in national building practices. These factors will be presented in more detail later in section 7.1. Finland is a part of the European Union; therefore, much of Finland's national legislation on energy efficiency of buildings is an outcome of energy policy coming from the European Council.

4 Energy performance of buildings

The energy performance of buildings entails several interesting topics. This section will begin by demonstrating the significance of energy use in the building sector. Next, building total energy use or E-value will be introduced. The discussion of building E-values will then logically transition into identifying building energy performance gap. After this, classification of buildings according to their energy performance will be shown. Last, renewable energy sources of high energy performance buildings will be discussed.

4.1 Energy use in buildings

In Finland, energy use in buildings accounts for 120 TWh per year or 38 percent of total energy use, and the building construction industry accounts for 4 percent of total energy use [18]. As figure 1 below identifies, there exists a great unrealized potential to reduce the primary energy consumption and environmental impacts of the building sector. Naturally, climate change and energy sustainability are two of the five main issues on the EU’s political agenda [10].

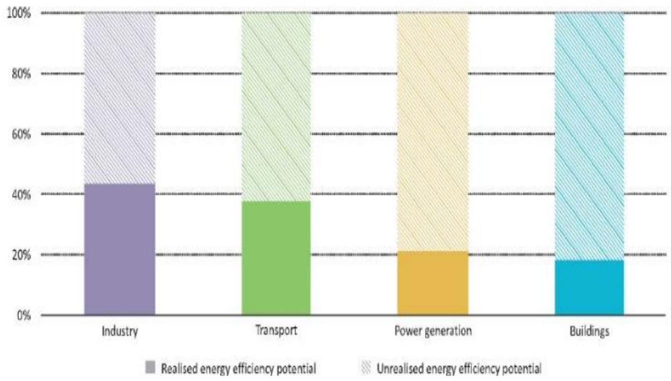


Figure 1. EU Energy saving potential in the four major sectors in 2015 [19]

In 2015 the volume of the building stock of Finland has been calculated to be approximately 560 million square meters in total, representing 369 billion euros [20]. Each year approximately 570 new office buildings are built in Finland (an annual increase of 1% or more of the cumulative 57 000 office buildings) [21]. The financial opportunities for realizing nZEB construction are significant with the climate-change-conscious directives, discussed in section 3.1, coming into effect.

4.1.1 E-value

In July 2012 the new building code of Finland (SRMK 2012) came into effect. One of the biggest changes in this new legislation was the shift to the total energy consumption analysis method (kokonaisenergiatarkastus). A building’s compliance of this section of the building code is demonstrated with the E-value calculation principle. The national building code of Finland gives the more precise definition of E-value as the total energy use of a building determined by the ratio of the predicted annual net energy imports multiplied by the energy carrier's energy factor all divided by the net heated floor area of the building (kWh/m^2·a^{-1}) [22].

Table 3. Office building E-values in Finland [17]

Office building E-values by the national building code of Finland (SRMK 2012)	
Energy performance class:	E-value [kWh/m^2·a^{-1}]
A	≤80
B	81 ≤ E-value ≤ 120
C	121 ≤ E-value ≤ 170
D	171 ≤ E-value ≤ 200
E	201 ≤ E-value ≤ 240
F	241 ≤ E-value ≤ 300
G	301 ≤ E-value

The 2012 Finnish building code categorizes new buildings into 9 building types each with individual E-values. E-value performance class levels range from A to G; with class A being the most energy efficient building per respective building category [22]. For new office buildings to receive building permission, the minimum allowable energy performance requirements are set by energy performance class C. As identified in the green area in table 3 above, annual primary energy consumption of offices must be less than or equal to 170 kWh/m^2 per year [17].

Advantages and disadvantages

The E-value performance indicator has two clear advantages. First, the E-value indicator provides a clear, easily comparable numerical value to show building owners the energy performance of their property, much like the energy performance declaration of household appliances or CO_2 emissions of a motor vehicle. Second, E-values incorporate the total energy consumption of a building including the secondary implications of CO_2 emissions from energy carriers. In this way the environmental impact from primary energy consumption has a great influence on design decisions of building projects, especially when comparing energy sources. [17] However, the E-value indicator has two disadvantages. First, building E-values only provide one aspect of a building's true environmental impact. E-values do not take into account the embodied energy of the building materials used to construct the building. Second, an E-value only indicates a building's predicted energy performance and the actual energy performance of the building has been shown in a recent study to be much greater [24]. The calculation of a building's E-value for a very simple case is given in equation (1) below.

$$E = \frac{\text{Edel,i} \cdot \text{fdel,i}}{A_{net}} \tag{1}$$

Where:

$E_{del,i}$ = is the final energy demand of energy carrier i [kWh/a];
$f_{del,i}$ = is the primary energy factor for demand energy carrier i;
A_{net} = the net heated floor area, [m^2]

The E-value calculation of a building supplied with district heating is given below with net heated floor area already included.

Net delivered energy

•	District heating	100 kWh/m^2, Primary energy factor of energy carrier = 0,7 (District heating)
•	Electricity	50 kWh/m^2, Primary energy factor of energy carrier = 1,7 (Electricity)

E-value = 100 (kWh/$m^{2}\cdot a^{-1}$) · 0,7 + 50 (kWh/$m^{2}\cdot a^{-1}$) · 1,7 = 155 (kWh/$m^{2}\cdot a^{-1}$)
For a more detailed calculation of primary energy indicator (E-value), refer to section 6.5: *Energy balance*.

4.1.2 Building Energy Performance Certificates

Building energy performance certificates (EPC) are documents which present a building's annual net primary energy consumption per net floor area (or E-value). As stated previously on page 12, for a new office building to receive a building permit in Finland, it must first demonstrate that its net primary energy consumption will be lower than the requirement of performance class C, and it must also fulfil two additional requirements. These two requirements of a building are compliance to building heat loss- and heating energy demand at design value requirements [21]. More information on these requirements can be found in the national building code of Finland section D3: Building Energy Performance.

In Finland the calculation procedure of the total energy consumption analysis method used in EPCs is specified by the Finnish Ministry of the Environment in the 2013 law

Ympäristöministeriön asetus rakennuksen energiatodistuksesta. When calculating a building's E-value the practitioner of the building EPC verification must use the most precise technical values of the building known. These values include the calculated amounts of heat losses, calculated annual primary delivered energy and calculated annual primary exported energy. If a design value is not known, then reference values from the Ministry of the Environment are to be used. [23]

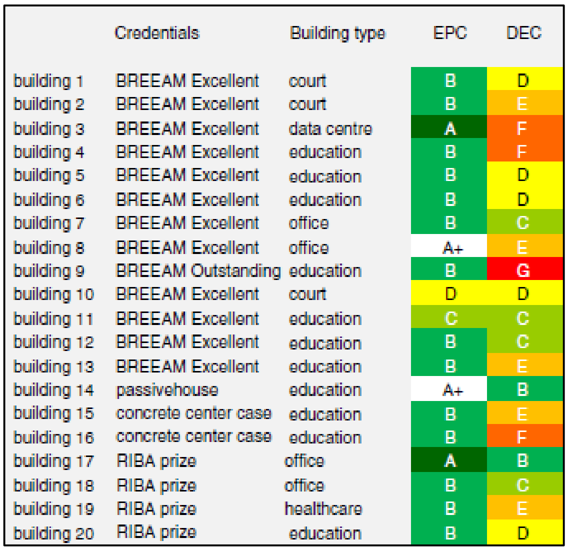
4.2 Energy performance gap

In a recent study de Wilde found that for high energy performance buildings such as nZEBs there is often a performance gap between the design energy performance and the actual measured energy use once buildings are operational [24]. The main reasons for this performance gap can be grouped into three categories causes from the design phase, causes from the construction phase (including handover), and causes in the operational phase of the building.

In the design stage two variables may lead to an energy performance gap later on lack of clear performance goals, and the imprecise simulation of actual energy performance. First, miscommunications between the client and design team about the building project's performance targets can lead to problems in reaching the quality requirements of the project. Second, in the design of buildings there is difficulty in accurately predicting the future energy use during the building use phase for several reasons. The actual energy use of the building is effected by a multitude of variables including occupant behaviour, occupancy schedule, internal heat gains, plug loads, climate, schedules of building service systems like HVAC, and also the maintenance of the building by facility management. [24]

Likewise, in the construction phase two problems most often lead to a performance gap. First, if the building is not constructed strictly in accordance to the design documents, then a reduction in building energy performance may result. If a builder neglects to produce the building strictly according to the design documents, often this causes in insufficient attention to be provided to both insulation and air tightness qualities of building envelope structures [24]. In a similar way, if the building envelope is not constructed following the designed thermal performance, then an energy performance gap will most likely result. For further information on the importance of thermal performance and air tightness qualities in nZEBs refer to section 6.3. Second, building energy performance may be effected by change orders and value engineering. When change orders and value engineering are applied to on-site renewable energy systems or other systems critical to the EPoB, an energy performance gap may occur. De Wilde points out that these problems are hard to notice, mainly because there is currently a lack of performance tests to assess the performance of newly constructed buildings [24].

In a recent study de Wilde compared the calculated annual energy consumption and actual measured energy consumption of 20 high performance buildings in the United Kingdom. Essentially, to measure the differences in energy consumption, UK Energy Performance Certificates (EPC) and Display Energy Certificates (DEC) were compared. As figure 2 below indicates 13 of 20 buildings examined experienced severe energy performance gaps. [24]



	Credentials	Building type	EPC	DEC
building 1	BREEAM Excellent	court	B	D
building 2	BREEAM Excellent	court	B	E
building 3	BREEAM Excellent	data centre	A	F
building 4	BREEAM Excellent	education	B	F
building 5	BREEAM Excellent	education	B	D
building 6	BREEAM Excellent	education	B	D
building 7	BREEAM Excellent	office	B	C
building 8	BREEAM Excellent	office	A+	E
building 9	BREEAM Outstanding	education	B	G
building 10	BREEAM Excellent	court	D	D
building 11	BREEAM Excellent	education	C	C
building 12	BREEAM Excellent	education	B	C
building 13	BREEAM Excellent	education	B	E
building 14	passivehouse	education	A+	B
building 15	concrete center case	education	B	E
building 16	concrete center case	education	B	F
building 17	RIBA prize	office	A	B
building 18	RIBA prize	office	B	C
building 19	RIBA prize	healthcare	B	E
building 20	RIBA prize	education	B	D

Figure 2. Comparison of EPC and DEC of 20 sample buildings [24].

In the UK, DEC is a more transparent building energy performance benchmarking tool which shows a building’s actual measured annual total energy consumption. Figure 2 above interestingly shows a dramatic decrease in performance rating classes of two *BREEAM Excellent* office buildings. One of these office buildings decreased its rating from the A+ to the E category, because of its severe energy consumption increase measured in its actual operational phase.

4.3 Classification

Nearly Zero Energy Buildings (nZEB) belong to the broader classification of high energy performance buildings. High energy performance buildings are buildings which incorporate state-of-the-art energy efficient building service systems through various sustainable strategies to reduce overall building energy use. These buildings are designed to optimize all building service systems and promote the health and productivity of occupants [25]. High energy performance buildings are classified according to their energy efficiency ratio for buildings (EERB) into three categories Zero Energy Buildings, nearly Zero Energy Buildings and plus energy buildings [26]. EERB is defined as the ratio of a building's energy required to energy used or ER/EU [27]. From figure 3 below the EERB is seen as the weighted energy demand factor (D) over the weighted export and generated energy factor (G).

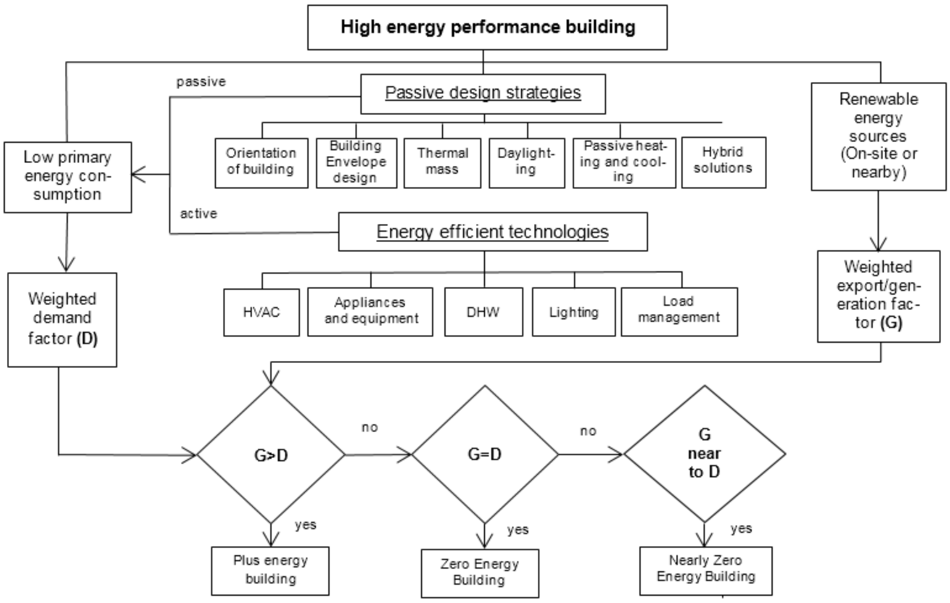


Figure 3. Classification of high energy performance buildings modified from original [26].

The process of designing high energy performance buildings is basically a two-step procedure. First, one must minimize the weighted energy demand factor (D) of the building with passive design strategies and energy efficient technologies. Passive design strategies include appropriate orientation of the building, building envelope design, thermal mass of building assemblies, daylighting strategies, other passive strategies such as passive heating and cooling and hybrid solutions [26]. Hybrid solutions are passive design strategies which do not utilize purely passive energy, but rather demand some supplemental energy for pumps and fans and also auxiliary devices.

Second, the generation of renewable energy should be designed so that the weighted energy export and generation factor (G) should approach the weighted energy demand of the building, D as close as possible. Energy efficient measures (EEM) for building services are applicable to any building services systems which consume energy including HVAC systems, DHW, lighting, appliances, equipment, and load management systems. EEM should be employed throughout a low energy building to lower the net energy demand [26]. The focus of this work is the third category of EERB, nearly Zero Energy Buildings (nZEB). More detailed information on the principles of nZEB may be seen in section 6.1.

4.4 Renewable energy sources

Finland is one of the Nordic countries lying between 60° and 70° N latitude in the northern hemisphere. The climate of Finland is a mixture between maritime and continental climates. This is mostly due to the effects of the Baltic Sea which warms the climate. The warmest month in Finland therefore never falls below 10°C (mean) and the coldest month never rises higher than -3°C (mean). Rainfall in Finland is moderate in all seasons. [28]

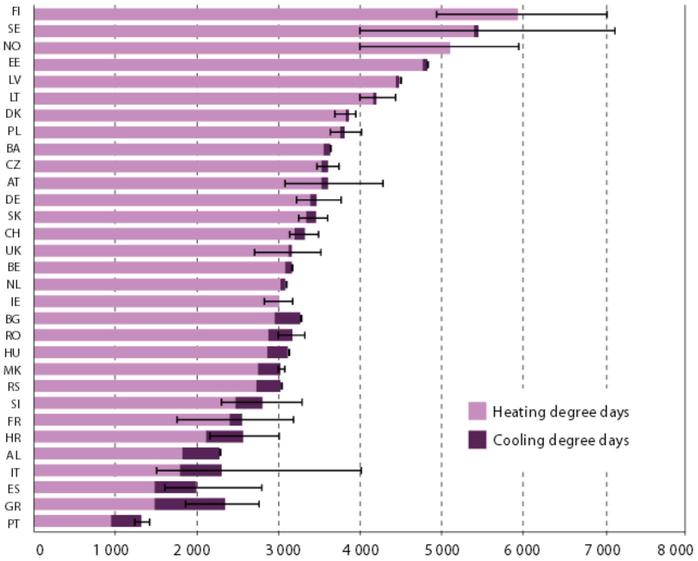


Figure 4. A comparison of average annual Heating Degree Days and Cooling Degree Days in Europe [29].

A comparison of the Heating and Cooling Degree Days for European countries is given in figure 4 above. A degree day is standard PI of heating or cooling used in quantifying the need of heating or cooling for a building. Heating Degree Days (HDD) are used to describe a building’s energy demand for space heating. A location’s HDD amount is found by combining the difference of the daily indoor and outdoor temperatures for each month [30]. As shown in figure 4 above, the sum of monthly HDD per year indicates that Finland has the greatest heating demand in Europe [30]. In any building project specifying which single or multiple renewable energy sources are the best solution should be carefully considered. Always the local environmental conditions, as well as city planning and other public authority regulations must be analysed to determine the extents of which forms of on-site renewable energy production are permitted. The production forms of on-site renewable energy sources in Finland summarized in table 4 below are solar energy, bioenergy, heat pumps and related devices, wind energy and hydropower. [17]

Table 4. Production forms of on-site renewable energy sources in Finland [17]

Production forms of on-site renewable energy sources in Finland	
Production forms:	
Solar energy	- Solar thermal energy - Solar electricity
Bioenergy	- Pellets - Wood chips - Biomass - Bio-oil - Bio-gas - Biofuels
Heat pumps and related devices	- Air heat pumps - Ground and water heat pumps - Ventilation extract air heat pumps - Air-to-water heat pumps
Wind power	- Small-scale wind power
Hydropower	- Small-scale hydropower

Out of the renewable energy resources feasible in Finland, solar energy has one of the greatest potentials with the sun providing 170 000 TW of solar energy per year [17]. However, the seasonal variations in solar irradiation are great especially in the northern parts of Finland. Table 5 below demonstrates the potentials of solar irradiation with seasonal variations and yearly averages. Solar irradiance is the measure of total irradiated energy per square meter transferred to a surface per year [17]. Global irradiation on a surface is the sum of all direct and diffuse solar radiation.

Table 5. Solar irradiation in Finland [17]

Global solar irradiation on horizontal plane for selected cities in Finland				
City:	Latitude: [°N]	Irradiation May-July [kWh/m^2]	Irradiation Aug-April [kWh/m^2]	Yearly irradiation average [kWh/m^2·a^{-1}]
Helsinki	60,2	160-170	**<30**	940
Jyväskylä	63,2	150-160	**<30**	870
Sodankylä	67,4	140-150	**<30**	780

Solar cooling belongs to the “heat pumps and other devices” category shown in table 4 on the top of this page. This is because heat driven solar cooling consists of two types of systems open and closed, which both use liquids to extract heat from the sun’s solar thermal energy [31]. The classification of heat driven solar cooling is shown in figure 5 below.

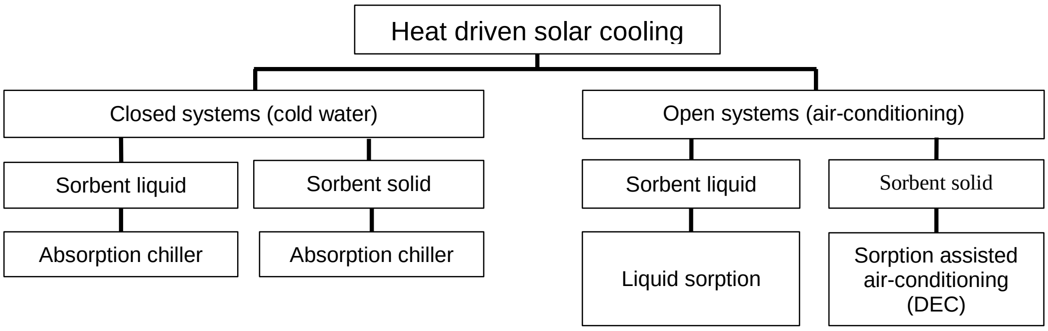


Figure 5. Heat driven solar cooling [31].

Cost optimal solutions

The FInZEB project work group found several general recommendations for cost optimal levels of renewable energy resources. First, the best way to reach cost optimality of Renewable Energy Ratio (RER) is to utilize already existing technology. Second, solar energy and waste water heat recovery technologies show great potential to lower building E-values. Third, the current energy performance requirements of the national building code, specific for office buildings are not very ambitiously set compared to the cost optimal level. [32]

5 Passive house buildings

Passive house concept, principles and definition

A passive house building is defined as a building which is designed to provide good indoor air quality and thermal comfort solely from heating or cooling of the supply air, without recirculated make-up air [33]. Passive house design is only one type of low energy building, but it is versatile and applicable worldwide and in different climates. In Finland the Paroc Passive House was the first passive house to be certified to the Passive House standard of the Passive House Institute (PHI) [33]. Construction of the Paroc Passive house in Tikkurila, Vantaa was completed in 2009. The building is a single family home as shown in figure 6 below. Further details of this project can be seen in table 6 below.

Figure 6. Paroc Passive House, Tikkurila, Finland [34].

Perhaps the most appealing attribute of the Passive House standard is that there are few mandatory requirements for Passive House standard certification. This provides design flexibility allowing the designer to focus on the main goals: to provide building occupants with good indoor environment and buildings that are honed for ultra-low building energy use. The requirements of a building to be Passive House standard certified are space heating energy demand is less than 15 kWh per square meter per year, primary energy demand is less than 120 kWh per square meter per year, airtightness is a maximum of 0,6 air changes per hour at 50 Pa pressure difference, and thermal comfort is ensured to be good year-round, not exceeding 25°C indoors 10% of a year [35].

Table 6. Design values of the Paroc Passive House [34]

Paroc Passive House in Tikkurila, Vantaa	
Building Attribute:	Design value:
External wall U-value	0,09 W/m^{2}K
Roof U-value	0,07 W/m^{2}K
Floor U-value	0,10 W/m^{2}K
Windows U-value	0,7-0,8 W/m^{2}K
Doors U-value	0,4 W/m^{2}K
Air exchange rate	0,5 times/h
Ventilation air flow (q)	0,075 m^3/s
Air tightness (n50)	n50 ≤0,60 1/h
Heating energy demand	18,7 kWh/m$^2 \cdot$a^{-1}

Passive house building today is mainly steered by the PHI; however, passive houses have been around long before these buildings were called passive houses [33]. Feist recounts that buildings preceding passive houses were found in different parts of the world, some built hundreds ago. For instance, the first Tulou traditional architecture, residential houses were built in southern China as early as the 15th century. It was common in these preceding passive houses, for the building to be heated once in the evening and the warmth would persists for long periods of time. [33] Since passive houses have been around much longer than ZEB and nZEBs, it is worthwhile to look at what exactly makes them function so well.

The five basic principles of Passive House standard design highlighted in figure 7 below are heat recovery ventilation, air tightness of the building envelope, thermal-bridge-free-design, increased thermal insulation, and Passive House certified fenestrations [33]. First, the building envelope elements must be very well-insulated in passive houses. The maximum heat flux density loss permitted across one square meter of exterior surface of a building element is 0,15 watts per degree of temperature difference [36]. Second, thermal bridges must be avoided in the planning of passive house buildings. Third, the air tightness of the building envelope is a very important component of passive house buildings, because uncontrolled air movement through the building envelope must be limited to ensure good indoor environment for building occupants. The air tightness (n50) requirement of the Passive House standard is less than 0,6 air changes of the total air volume of the building per hour. After a passive house building is constructed, the air tightness of the building envelope will be tested at both 50 Pa overpressure and under pressure. Fourth, the air tightness of fenestrations must also comply with the 0,6 air changes per hour requirement. Window assembly air tightness is based on simulated internal and external pressure coefficients dependent upon building plan and height [36]. In addition, the window frames of passive house windows must be very well insulated and have low-emissivity-glazings. Last, the ventilation heat recovery plays a vital part in ensuring the high energy performance of passive houses. The requirement of the Passive House standard is that at least 75% of the heat from extract air is recouped to preheat the supply air [35]. All of these five grounding principles of passive house design should be looked at when planning a nZEB since passive house and nZEB projects have very similar building energy performance goals.

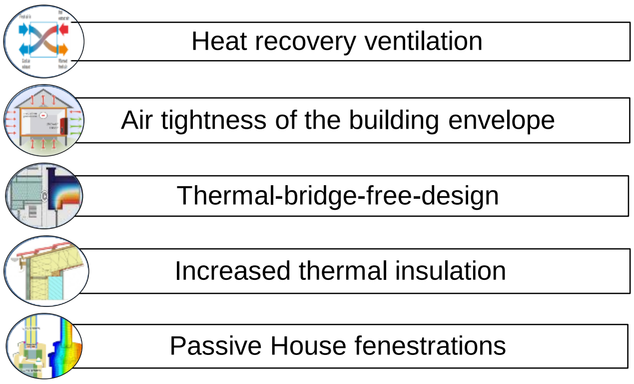


Figure 7. The Passive House standard design principles [33].

6 Nearly Zero Energy Buildings

There are several aspects that interact with one another to shape the definition of nZEB. The four aspects that should be considered when forming national definitions of nZEB according to the Buildings Performance Institute Europe (BPIE) are presented in figure 8 below. The four aspects that should be weighed equally are financial and market aspects, political and legal aspects, technical aspects, and environmental and societal aspects [12]. Forming national nZEB definitions from a balanced view of all four aspects enables each EU country to find a complete definition of nZEB which is challenging, but economically feasible.

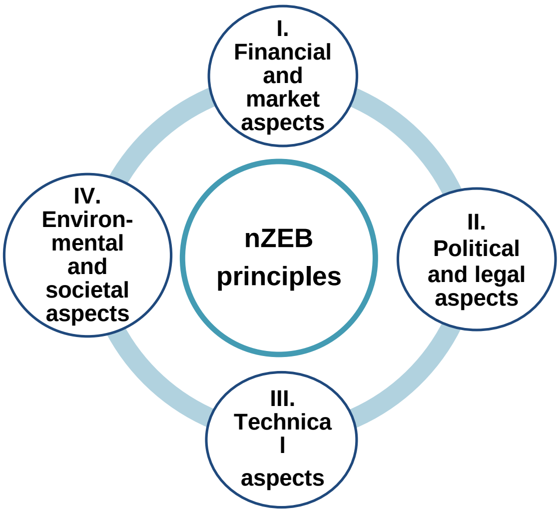


Figure 8. The four principles of nZEB [12].

Looking back at the EPBD recast presented in section 3.3, nZEBs have three main principles energy demand, renewable energy share and primary energy and CO_2 emissions [12]. First, the system boundaries of energy flows must be able to describe the building's primary energy demand clearly. Moreover, the threshold value for maximum energy demand of nZEBs must be determined. Second, the system boundary must also be defined to include energy flows of renewable energy production on-site or nearby. Similarly, the minimum share of energy from renewable energy sources must be defined. Third, the system boundaries of energy flows must be agreed to include overarching primary energy demand and CO_2 emissions. Last, the minimum amount of overarching primary energy demand and CO_2 emissions must be defined.

6.1 Planning phase

There have been numerous previous studies on nZEB projects mainly focusing on the planning phase. Paulson found already in the 1970's, that the investment of additional time and capital early on in a building project has the greatest positive impact on the success of the building project [37]. According to the graph in figure 9 below, the cost of design changes are the lowest, whilst the ability to impact the building project are greatest in the building phases preceding the construction phase. Especially in high energy performance building projects, the investment of additional time and capital in the design stage is the most worthwhile effort in aiding a building project meet its building energy performance requirements [24].

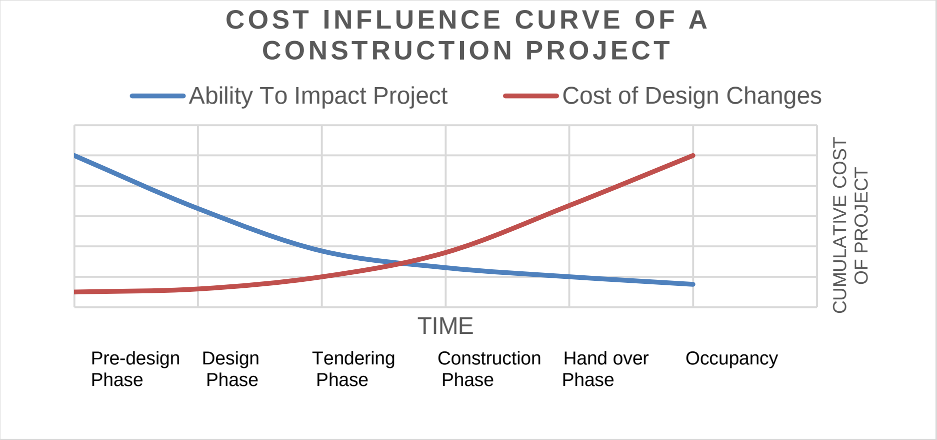


Figure 9. Cost influence curve of a construction project [37].

In the planning phase there are several productive tools which are both value-driven and performance-enhancing. The financial sector provides several universally known financial theories which can be utilized in the construction industry. One such methodology is Life Cycle Costing analysis commonly referred as LCC. LCC is defined as a long-term evaluation approach that assesses the most cost-effective asset or design over a time frame examined [38]. The life cycle costs of an asset are equal to the net sum of the asset's costs over the duration of its life cycle considered, including initial costs, operation and maintenance costs (O&M costs) and the residual value of the asset at the end of its useful life minus any disposal costs [39]. LCC has been shown by several studies to be an advantageous tool saving total costs over the lifetime of a building [40; 41]. Consequently, it is becoming more and more common for building owners and designers to use LCC to make informed decisions for building design choices [40]. Yet, there are still clients who are ignorant of the benefits of LCC giving it a low priority in their decision making influences. One disadvantage of LCC is that it needs a great amount of time and effort. For that reason, LCC must have an easily understandable output motive for it to become a standard practice in the construction industry. [42]

Another tool which aids a building project reaching quality and energy performance goals is building commissioning. Building commissioning is a project management tool which is simultaneously also a supplemental quality assurance process. ASHRAE defines commissioning as a quality assurance process for enhancing the delivery of a project. Commissioning entails the processes of verifying and documenting that the facility inclusive of all systems and assemblies are planned, designed, installed, tested, operated and maintained to fulfil the client’s quality requirements [43]. Typically, a commissioning lead consultant is responsible for guiding a building project through the commissioning process to reach its quality and performance goals [44]. Commissioning consultants work for the owner of a building to guarantee that the building will perform and operate as designed and that the facility management staff are trained and qualified to operate and maintain its building systems [43].

Commissioning has been found in several studies to be cost effective [45; 46]. In a recent study Mills found commissioning costs of a new building to be 11,89€/m^2 on average with a payback time of the entire building project to be 4,2 years; resulting in a median whole building energy savings of 13% [45]. Additionally, commissioning has been shown by Mills to lower risk in building projects [47]. This is especially pertinent for complex green building projects with high performance targets such as nZEBs. In fact, Yang and Zou state that both researchers and builders find green building projects to be more complex and prone to increased risk [48]. They argue that the main reason for this is that the construction industry is very conservative, is limited by the inadequate transfer of technology from other sectors in society as well as slow changes from government.

Kantola found commissioning to be an excellent tool to guide a high performance building project such as an nZEB [49]. Furthermore, the benefits of commissioning are so well recognized internationally that building commissioning is a mandatory process in all LEED environmental rating systems to receive LEED certification. [50] The process of commissioning is given in figure 10 below. Retrocommissioning is a secondary application of the commissioning process when an existing building seeks to improve its building systems or systems function altogether [47].

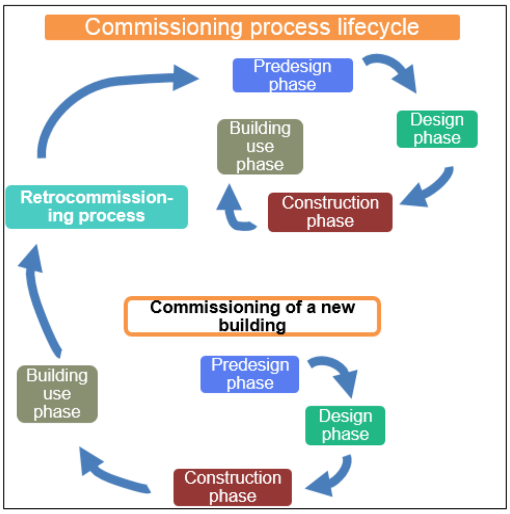


Figure 10. The commission process lifecycle.

6.2 Design principles

There exists a vast amount of literature on the design principles of high energy performance buildings for example by [26] and the successful implementation of building projects including nZEBs [51]. Andresen focused on design processes involved in low energy buildings, but from exclusively the passive design philosophy [52]. The main framework of the design process of low energy buildings was most notably illustrated by Andresen's Kyoto pyramid seen in figure 11 below. The Kyoto pyramid suggests a streamlined design flow for energy efficient buildings with solely passive design elements.

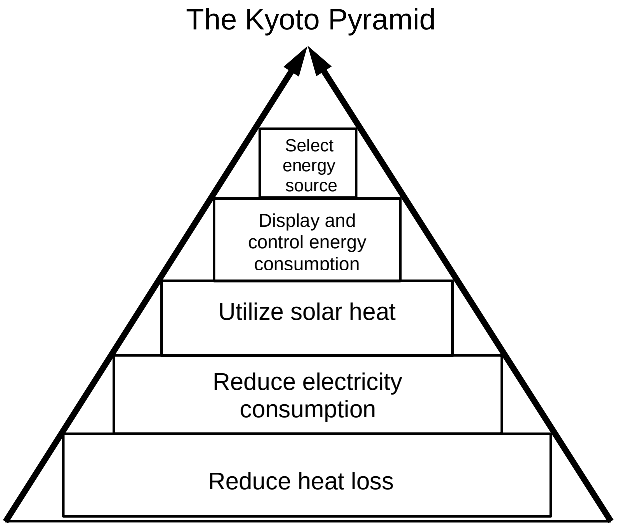


Figure 11. The Kyoto pyramid [52].

The Kyoto pyramid was developed for building designers to create a new focal point for the design process: the incorporation of passive design strategies throughout the building. These passive design strategies consist of five steps [52]. The first step is to reduce heat loss through the building envelope and heat loss of HVAC systems. The second step is to reduce the energy demand of the building. The third step is to utilize solar heat gains and the thermal energy of the sun. The fourth step is to control energy consumption and display energy use to building users. The last step is to select an energy source suitable for the building and the local environment. While the Kyoto pyramid emphasizes the use of passive design strategies it is sometimes also beneficial to include technology into the design of low energy buildings. [53]

Next, Heiselberg revisited the Kyoto pyramid in creating the IBC Energy design pyramid to include design strategies and technology, see figure 12 below. An example of these new technologies are Responsive Building Elements (RBE). A RBE is defined as a building element that adapts its functionality to internal or external changes and to occupant intervention in order to maintain an appropriate balance of the Building Management System (BMS) [53]. These building elements may include: advanced integrated facades, thermal mass activation, earth coupling, Phase Change Materials (PCM) and dynamic insulation [53]. An example of thermal mass activation of concrete may be seen in section 8.1.

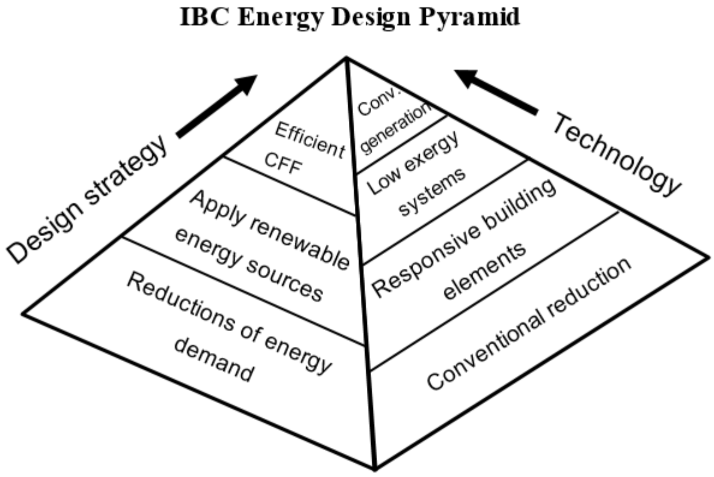


Figure 12. IBC Energy design pyramid [53].

In general, the strategy to reduce primary energy consumption in a building is a three-step system apply EEM to reduce heating and cooling demand, utilize an optimal share of renewable energy production, and meet the residual energy demand of the building with an energy efficient supply system. Low energy building design should focus on four cardinal principles reducing heat losses, reducing cooling demand, reducing electricity consumption, and comparing environmental impacts of energy sources. These four cardinal principles are listed below.

Reducing heat losses

- Building geometry ratios and orientation
- Building envelope design
- Air tightness
- Heat recovery ventilation

Reducing thermal energy demand

- Minimize cooling demand in cooling season
- Minimize heating demand in heating season
- Utilize thermal mass
- Utilize Responsive Building Elements (RBE)

Reducing electricity consumption

- Energy efficient lighting and equipment
- Daylighting strategies
- EEM in HVAC

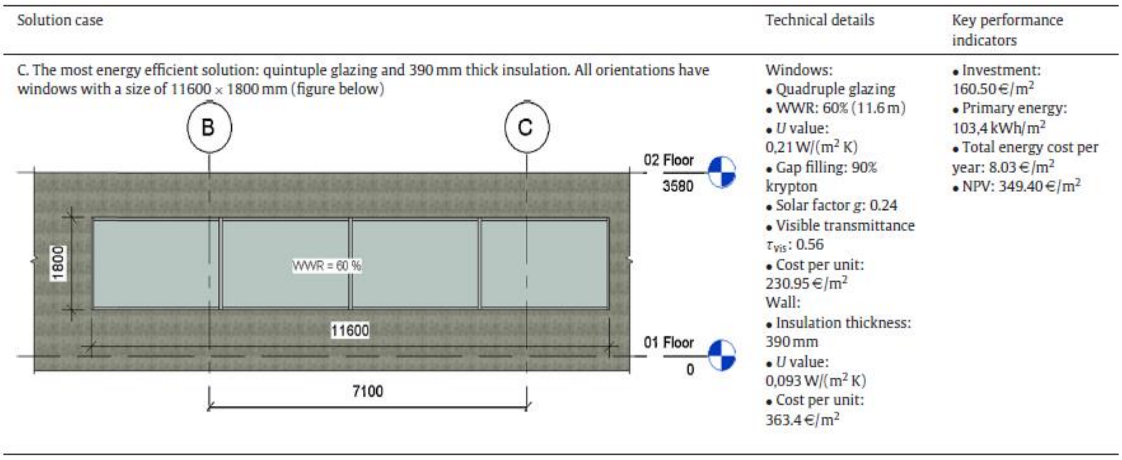
Comparing environmental impacts of energy sources

- Finding the cost optimal share of renewable energy ratio (RER)
- Utilizing best available state-of-the-art technologies and renewable energy sources most suitable for local environmental conditions

In review, there are several methodologies describing low energy building including the Kyoto and IBC energy design pyramids. All in all, there are four cardinal principles of low energy buildings which are indispensable in ensuring high energy performance. These four principles are reducing heat losses, reducing thermal energy demands, reducing electricity consumption, and comparing environmental impacts of energy sources.

6.2.1 Thermal performance of building envelopes

When designing an nZEB or any low energy building for that matter, heat losses should be reduced in the building envelope, the HVAC system and air infiltration. Significant energy demand reductions through building envelope heat losses can be achieved with correctly designed building envelopes. In a recent study Pikas, Thalfeldt and Kurnitski examined cost optimality and nZEB solutions for office buildings in Estonia. In their study they found the modelled external office wall with quintuple glazing, 390 mm thick insulation and the minimum amount of fenestrations to be the most energy efficient solution [54]. The technical details and PI are given in figure 13 below.



Solution case	Technical details	Key performance indicators
C. The most energy efficient solution: quintuple glazing and 390 mm thick insulation. All orientations have windows with a size of 11600 × 1800 mm (figure below)	Windows: • Quadruple glazing • WWR: 60% (11.6 m) • U value: 0,21 W/(m^2 K) • Gap filling: 90% krypton • Solar factor g: 0.24 • Visible transmittance τ_{vis}: 0.56 • Cost per unit: 230.95 €/m^2 Wall: • Insulation thickness: 390 mm • U value: 0,093 W/(m^2 K) • Cost per unit: 363.4 €/m^2	• Investment: 160.50 €/m^2 • Primary energy: 103,4 kWh/m^2 • Total energy cost per year: 8.03 €/m^2 • NPV: 349.40 €/m^2

Figure 13. Energy efficient fenestration design solution for a low energy office building [54].

In effect, the total thermal transmittance (U-value of a building assembly) is the physical property which has the greatest effect on energy demand related to a building's interior thermal comfort. Three other physical properties that also affect interior thermal comfort are radiation surface absorptance, thermal lag and thermal energy storage capacity of buildings. [26] Insulated concrete external building walls with high thermal mass have been shown in a study by Zhu, Correia and Boehm to decrease energy consumption used for building heating and cooling [55]. Essentially, buildings with a significant ratio of thermal mass containing structures experience a greater thermal lag or daily fluctuation in interior temperatures [56].

Thermal transmittance

Wit defines thermal transmittance, also called composite thermal conductance or U-value, as the overall thermal transmittance measuring the rate at which thermal energy is transferred through a building element such as a wall or complete building assembly [W/(m^2 ·K)]. It is the summation of all combined thermal resistances of all the elements in a construction, including surfaces, air spaces, and the effects of any thermal bridges, air gaps and fixings. [56] Essentially, the thermal resistivity of building materials such as thermal insulation create the largest impact in the heating demand of buildings. In opaque building envelope structures or structures which trap solar radiation such as external walls, the U-value of these building elements should be as low as possible indicating a good level of resistance to heat loss through the building envelope. In non-opaque building envelope elements such as fenestrations, additional variables must be taken into account such as total solar heat transmittance (g-value) and shading coefficients [56].

Thermal bridges

The second step to reduce heat losses through building envelopes is to minimize thermal bridges in structures. A thermal bridge occurs when the local density of heat flow rate of a particular entity within the building envelope is significantly larger than at one or more adjacent entities [36]. Thermal bridges occur in planes across a layer in a structure, at corners between planes across two building elements, and wherever a structure penetrates the continuity of the thermal insulation layer. Thermal bridges have three major drawbacks extra heat loss of a structures, a high surface relative humidity locally at the thermal bridge on the exterior or interior surfaces of the building (cold-bridge condensation) resulting in moisture problems, corrosion, and interstitial condensation when warm, moist air penetrates into a building element, reaches a dew point and condensates into water causing increased risk of mould, rot, and moisture problems. [57]

6.2.2 Air tightness of building envelopes

Building envelope air tightness in low energy buildings should considerably greater than building envelopes in reference to buildings designed to the building code values [58]. In Finland the building code requirement for air tightness (n50) is 0.5 air changes per hour measured by building pressurization tests. The effect of uncontrolled air leakage is a serious issue further multiplied in buildings with low air exchange rates and during the heating season in cold climates. The vapour content of indoor air is higher than that of air outside the building envelope. This is because indoor areas of buildings are closed environments which contain several sources of water vapour including people, cooking, and plants.

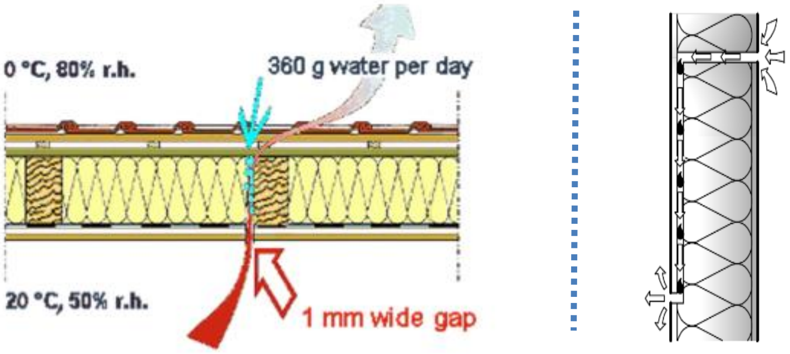


Figure 14. Air leakage through external wall constructions. The effect of extended path of air travel on the cold side of external walls results in moisture condensation [33 (right); 59 (left)].

The effects of uncontrolled air leakage through the building envelope lead to condensation of water vapour inside the external wall structures. This is demonstrated in figure 14 below, where warm indoor air cools as it exfiltrates across the building envelope through a 1 mm wide gap across 2,5 meters of an external wall, in a cold climate. The warm water vapour then condensates at a certain distance inside the external wall. For each day it is estimated that 360 grams of water condensates in the structure [33]. This condensation leads to moisture problems such as mould growth, rotting of organic materials, and corrosion of metal fasteners and other metal building products. [57]. Moisture problems are known to lead to significant indoor air problems which are hazardous to the health and well-being of building occupants and additionally lower the real estate value of properties.

6.3 HVAC systems

In a recent study Enteria and Mizutani found that half of the energy consumption of commercial buildings is used by HVAC systems [60]. Thus, the design process of low energy buildings as discussed in section 6.3 should start with reducing heat loss of HVAC systems and reducing energy consumption of buildings. The process of specifying which type of HVAC system is most suitable for a given building is a demanding exercise requiring LCC analysis, energy savings comparisons, as well as other internal and external variables. A list of strategies to lower energy consumption of HVAC systems is shown below [61].

Energy efficient HVAC strategies:

- Direct evaporative cooling (DEC) systems
- In direct evaporative cooling (IEC) systems
- Evaporative-cooled air conditioning systems
- Liquid pressure amplification (LPA) systems
- Thermal storage systems
- Heat recovery systems
- Ground-coupled systems
- Chilled ceiling systems
- Desiccant cooling systems

HVAC systems of nZEB buildings must be designed well and have heat recovery ventilation. The heat recovery rate of the heat recovery unit (HRU) must be as high as cost optimally possible, but at least 85% in cold climates like Finland. Furthermore, all details must be designed, including detailed construction plans of locations where HVAC ducts penetrate the building envelope. Additionally, in mechanical ventilation systems the correct sizing of the HVAC system components such as specific fan power (SPF) of the air handling unit is very important to minimize HVAC energy consumption.

6.4 Energy balance

NZEB buildings are in most cases defined by a balanced energy budget that is measured over one year. The energy need for the building is based on regional meteorological data for a typical year, often a Test Reference Year (TRY) at the location. The TRY is not an extreme weather year. Eike, Musall and Lichtme point out that during the use phase of a building different ends of the weather spectrum may be experienced, thus the energy budget may be balanced in some years and not in others. [14]

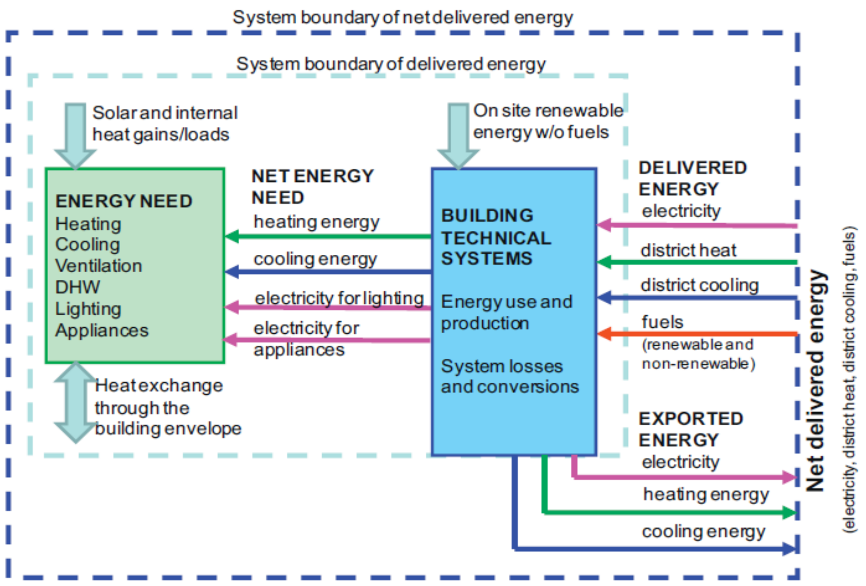


Figure 15. System boundary of nZEB [62].

The energy flows of an nZEB within its system boundary are shown in figure 15 above. As mentioned previously in section 4.1.1, the accounting of a building's calculated annual energy consumption does not include embodied energy. Embodied energy is energy contained within building materials from their production, energy required for replacement, and energy required on renovation acquisitions during a building's lifetime. Eike et al. found embodied energy to be quite substantial; the value of embodied energy of an energy-efficient building is equivalent to 20 to 30% of its total primary energy consumption over an 80 year lifecycle. [14]

Net primary energy demand

Basically, the net primary energy consumption of the nZEB is calculated by the difference of delivered energy minus exported energy. The net delivered energy is defined as the difference of delivered - and exported energy, calculated inclusive of primary energy factors for energy carriers [62]. Primary energy demand of a building is calculated as shown in equation (2) below.

$$E_P = \sum(E_{del,i} \cdot f_{P,del,i}) - \sum(E_{exp,i} \cdot f_{P,exp,i}) \qquad (2)$$

Where:

E_p = Primary energy demand [kWh/ a];

$E_{del,i}$ = final energy demand of energy carrier i [kWh/a];

$f_{del,i}$ = primary energy factor for demand energy carrier i;
$E_{exp,i}$ = final energy export of energy carrier i [kWh/a];
$F_{exp,i}$ = primary energy factor for export energy carrier i

The primary energy factors of energy carriers used in energy calculations in Finland are presented in table 7 below.

Table 7. Primary energy factors of energy carriers in Finland [23]

Energy carrier	Energy factor
Electricity	1,7
District heating	0,7
District cooling	0,4
Fossil fuels	1,0
Renewable fuels used in the building	0,5
Renewable energy production	No factor

Taking equation (2) above one step further and dividing by the net heated area produces equation (3): primary energy indicator (primary energy rating of a building) [62].

$$E = \frac{\sum_i \left(E_{del,i} \cdot f_{P,del,i}\right) - \sum_i \left(E_{exp,i} \cdot f_{P,exp,i}\right)}{A_{net}} \tag{3}$$

Where:
E = Primary energy indicator [kWh/m^2 · a^{-1}];
$E_{del,i}$ = final energy demand of energy carrier i [kWh/a];
$f_{del,i}$ = primary energy factor for demand energy carrier i;
$E_{exp,i}$ = final energy export of energy carrier i [kWh/a];
$F_{exp,i}$ = primary energy factor for export energy carrier i;
A_{net} = the net heated floor area, [m^2]

An example of the Viikki Ympäristötalo office building's energy balance is given in table 8 below. The Ympäristötalo is a low energy office building with on-site renewable energy production located in Helsinki, Finland, built in 2011. The primary energy rating of the building is 85 kWh/m^2 per year (inclusive of weighted effects of energy carrier's energy factors) [62]. According to the E-values recommended by the FIn-ZEB project, the Ympäristötalo would be classified to be an nZEB office building in Finland, permitting that the share of renewable energy set by the next national building codes is less than the production share for this building.

Table 8. Energy balance *of the Ympäristötalo office building [62]*

Energy performance (simulated) of the Ympäristötalo office building, Helsinki, Finland.				
Building services and energy production	Net energy need $[kWh/m^2 \cdot a^{-1}]$	Delivered energy $[kWh/m^2 \cdot a^{-1}]$	Energy carrier's energy factor	Net primary energy $[kWh/m^2 \cdot a^{-1}]$
Space and ventilation heating (MVHR)	26,6	32,2	0,7	22,6
Hot water heating (DHW)	4,7	6,4	0,7	4,3
Cooling	10,6	0,3	1,7	0,5
Fans and pumps	9,4	9,4	1,7	16,0
Lighting	12,5	12,5	1,7	21,3
Appliances (plug loads)	19,3	19,3	1,7	32,7
On-site Photovoltaic energy production		-7,3	1,7	-12,0
Total	**83**	**73**		**85**

As illustrated in table 8 above, the energy needs of the building are met by energy flows within the system boundary constituting a mixture of both on site renewable energy and delivered energy [62]. The calculated Renewable Energy Ratio (RER) for this office building is only 20%, not including energy from the ground-source heat pump. For more information on RER principles and calculation methods refer to section 6.6.

Load match

Load matching is defined as the process aiming at minimizing the fluctuation of on-site energy production to primary energy consumption [63]. Load matching compares the amount of on-site energy produced with the governing building energy consumption loads over a set time period. There are performance indicators (PI) available to describe the efficiency of a building's load matching called Load Matching and Grid Interaction Indicators (LMGII). One useful LMGII which describes the relative proportions of both electricity generated and electricity consumed is called load match index ($f_{load,i}$) [14]. The calculation methodology for load match index is given in equation (4) below.

$$f_{load,i} = min\left[1, \frac{on\text{−}site\ electricity\ generation}{electricity\ consumption}\right] \cdot 100[\%] \tag{4}$$

Where:

i = time interval (hour, day, month)

Eike, Musall and Lichtme found that for a Zero Energy Building (ZEB) with a photovoltaic system that meets its annual electricity demand, the load match index is of the order of 60 to 80% [14]. In the best case ZEBs if the time interval is shortened to instantaneous level electricity metering, or *net metering*, the load match indices of the building's energy flows near 30%. However, in ZEBs without load management and on-site electricity storage, the load match index may fall even lower. In this case, the building peak loads and dependence on grid electricity at night cause the building to report low instantaneous load match indices [14]

6.5 Renewable energy sources

As stated in section 3.3, the EPBD recast requires building designers provide calculations for the Renewable Energy Ratio (RER) of buildings. RER expresses the ratio of energy produced from renewable energy sources considering total primary energy consumption of a building. In RER all energy flows within the system boundary are used in accounting and exported energy is subtracted from delivered energy [64]. The calculation methodology for RER is given in equation (5) below.

$$RER_p = \frac{\sum_i E_{ren,i} + \sum_i ((f_{del,tot,i} - (f_{del,nren,i}) \cdot E_{del,i})}{\sum_i E_{ren,i} + \sum_i (E_{del,i} \cdot f_{del,tot,i} \cdot) - \sum_i ((E_{exp,i} \cdot f_{exp,tot,i})} \tag{5}$$

Where:

RER_P is the renewable energy ratio based on the total primary energy,
$E_{ren,i}$ is the renewable energy produced on site or nearby for energy carrier i, [kWh/a];
$f_{del,tot,i}$ is the total primary energy factor (-) for the delivered energy carrier i;
$f_{del,nren,i}$ is the non-renewable primary energy factor (-) for the delivered energy carrier i;
$f_{exp,tot,i}$ is the total primary energy factor (-) of the delivered energy compensated by the exported energy for energy carrier i;
$E_{del,i}$ is the delivered energy on site or nearby for energy carrier i, [kWh/a];
$E_{exp,i}$ is the exported energy on site or nearby for energy carrier i, [kWh/a].

7 Quality and quality assurance in construction

Construction of building projects with high quality and energy performance requirements must entail essential certain structured managerial procedures. In this section first quality in building projects will be introduced. Second, quality assurance of building projects will be discussed. Third, quality assurance on nZEB building sites will be presented. Last, the most important points of nZEB building project management will be shown.

7.1 Quality

Quality is defined as the features and qualities of a product or service which fulfil its predetermined or assumed needs [65]. In construction projects, before any transaction between two parties may proceed, a clear and mutually understood definition of quality of a product or service must be expressed. A definition of quality can be expressed in many ways, but most important is to state the methods in which the set quality requirements in each specific case will be validated. Similarly, the principles of a quality assurance system which maintain its operation during the course of the project must be ensured [66].

7.2 Quality assurance

Quality assurance maybe defined as a framework to guarantee requirements of both quality and performance of a building specified by the owner are transferred to the building design documents and later to the attributes of the constructed building [66]. In the quality assurance of a construction project careful consideration and attention to detail is required especially in work which is demanding, difficult or costly to repair or may have significant effects on meeting the quality goals of the project [66]. In other words, it is advisable to ensure risk mitigation practices with careful planning of the construction phases which have the potential to effect subsequent tasks from reaching their quality goals. Perhaps most importantly in the planning of a construction project, enough resources, especially time in the project schedule, and supervision must be allotted to each construction phase. This ensures that all construction phases will be completed according to their individual specifications and quality goals.

Goals of quality assurance

There are two main goals of quality assurance in construction projects. The first goal of quality assurance is to strive to produce a product or service, in the first attempt, which meets the client’s and users’ quality expectations [66]. Thus, it is mutually beneficial for both the supplier of the product or service and the building owner that the product or service manufactured or completed is done so in strict accordance to the project planning documents. In addition, the product or work provided should be able to be described according to quality and finished work should not have significant variation in quality. [66] The second goal of quality assurance is to verify that the final work produced for each construction phase is completed according to the design documents and by following legal construction regulations and practices [66]. Written procedures must be in place to ensure that quality assurance is met especially in tasks in which the internal structure will subsequently become hidden. Quality assurance procedures must be able to decrease the likelihood of delays and other problems through examination of work quality that has immediate effects on subsequent construction phases as well as the turnover phase.

Quality assurance in the planning phase

The quality requirements of a construction project are first brought up in the in planning phase. For quality to be ensured quality guarantees must be expressed clearly in planning documents. Planning documents should reference product standards, product specific installation and working method instructions or quality standards of construction tasks such as RYL 2000 quality standards in Finland [66]. Documents required in the planning documents package include: the quality plan, quality guarantees for specific construction phases and other official procedures for verification, and documentation of quality assurance throughout a construction project [67].

Quality guarantees are given by the main contractor and the quality requirements of the building owner are written into the quality plan. When quality guarantees are expressed between parties, it must be verified that every party who may have an effect on the final result is supplied with and understands the information necessary to meet the quality requirements of the product or completed work [67]. Another important document in the quality assurance process is the quality plan. The quality plan includes a general description, risk analysis, project controlling documents, written co-operation guidelines, a quality assurance plan, turnover phase quality assurance documents, and other documentation [67].

In Finland, the construction industry’s general terms and conditions (YSE 1998) give the requirements for construction contracting. In section nine, the general conditions of quality assurance by the client are given [68]. The client must ensure that all of the required conditions in section eight are fulfilled so that the builder has all the prerequisites to fulfil their contractual obligations. Furthermore, this document provides the guidelines for third-party verification consultant work on construction sites [68]. These verification inspectors represent the interest of the client, but may also be hired to represent the builder or another client such as a public client (municipality or city). The verification inspector has the following right: to visit construction sites were the construction project is being completed, complete measurements and field tests required to ensure that the quality of the construction phases are completed according to the quality plan and building codes, and receive the quality assurance documents from the builder upon request. Also, the verification inspector has the obligation to inform the builder, verbally or in writing, of any mistakes in construction phases which may lead to additional costs, danger or damages. [68]

Quality assurance in nZEB projects

In high energy performance building projects, formation of the quality assurance plan should have three perquisites. First, the energy performance goals of the building project should be determined as early as possible in the design phase. Second, the energy performance goals of a building project should follow guidelines conformed to the building project type, during the design phase, construction phase, and handover of the project and building use phase. Third, the energy performance goals of the building project should be monitored before handing over the building to the client in the final commissioning of the building. [69]

Quality assurance of passive house projects is generally regarded to require a higher level of control. Therefore, quality assurance plans from the Passive House standard certification process may be applied to nZEB projects [17]. Considerations of planning qualities of a high energy performance building can be divided into four sections planning of the building structure (architectural and structural design), planning of the HVAC systems, planning of the electricity systems, and planning of the energy use of the building [68].

In implementing the planning of the building structure, every aspect of the structure should be well designed and examined rigorously, especially the building envelope. Effectively, five things should be focused on highly insulated standard constructions, avoiding thermal bridges, air-tight connection details, window optimization, and calculation of the specific energy demand of the building. The quality assurance for thermal bridge free connections should be to calculate thermal bridges across all connections or demonstrate thermal-bridge-free-design [70]. Similarly, for complete window assemblies, performance properties should be checked including glazing type, frame connections, glazing ratio, and solar protection. Also, a quality assurance test should be performed for the calculation of energy demand following the Passive House Planning Package design tool (PHPP).

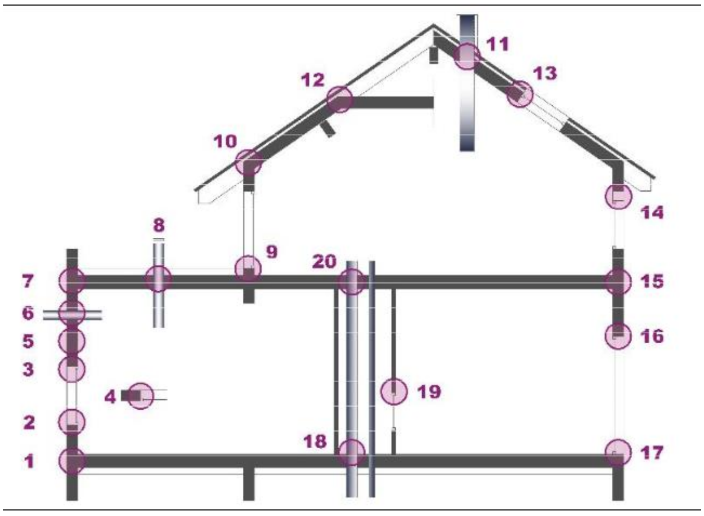
Next, in the ventilation system quality assurance checks should be performed already in the planning phase of a building project. An expert of passive house building design, Feist gives several checks that should be completed. Feist states that in designing ventilation systems for passive houses, the placement of ductwork should be positioned as energy efficiently as possible. This means that warm extract air ducts should be located inside of the envelope as much as possible, and in locations where this practice is not possible, they should be short and very well insulated to avoid a temperature gradient from cold to warm spaces. Next, the efficiency of the heat recovery unit should be greater or equal to 75%. The ventilation system should be airtight with recirculated air less than 3% and electrical efficiency should be less than 0, 4 Wh/m^3 [70]. Additionally, the ventilation system should be balanced correctly since passive house building envelopes are more air tight than those of buildings constructed to the standard building code. If the ventilation system is not properly balanced, it can lead to adverse effects especially undesired hygrothermal behavior within the building envelope [56].

Then, the implementation of the other building service systems should be carefully managed. Special consideration should be given in the design drawings of plumbing services including supply water pipes, drainpipes, heating pipes and any locations where pipes penetrate the building envelope. Domestic hot water (DHW) pipe layout should be as short as possible and the pipes should be well insulated. Additionally, drainpipe layout should be short and drain ventilation pipes should preferably terminate at roof vents or insulated vent pipes [70]. Instances where plumbing or electrical installations are required to pass through building structures, should be designed to create minimal penetrations in the building envelope. However, when it is necessary to penetrate the building envelope, great care should be exercised to ensure that the air tightness and thermal properties of the building envelope remain uniform [58]. In conclusion, quality control should be performed on all of the building service systems.

7.3 Quality assurance on a nZEB jobsite

In a well-managed construction project, the quality assurance process should follow continuously throughout the construction phase with quality assurance tools on the construction site. Quality assurance tools on site include task plans, task starting meetings, inspection of the first working unit, model room and documentation of structures that will become hidden, quality assurance matrices, operational tests and self-turnover checks of completed construction tasks [66]. In buildings there are numerous locations where documentation of structures that will become hidden is required. An examples of hidden structures can be bathroom moisture sealing. For instance, after the bathroom moisture sealing task is completed, the thickness of the sealant should be determined to be according to the manufacturer's recommendation before the tile laying task may be started.

For the quality assurance of the building envelope structure, several things should be ensured absence of thermal bridges, uniformity of insulation layers, and airtightness. The locations in the building envelope which are most prone to air tightness problems are depicted in figure 16 below. Basically air tightness problems most commonly occur in junctions of structures within the building envelope [71]. Common locations of inadequacies of air tightness are around fenestrations (both external walls and roof structures), around external doors, intersections between building envelope assemblies such as junctions between external walls and roof structures, and around any penetrations through the building envelope such as plumbing and HVAC ducts.



Number	Intersection point
1	Foundation slab /external wall
2	Window/external wall
3	Window/external wall
4	Window/external wall
5	External wall cross section
6	Hole or slit external wall
7	Top floor/external wall
8	Penetration top floor
9	Window/external wall
10	Roof/external wall
11	Penetration roof
12	Roof/roof ridge
13	Roof/window
14	Window shading device/external wall
15	Intermediate floor/external wall
16	Door/external wall
17	Door/sill
18	Foundation floor/crawlspace
19	Service shaft/door
20	Other

Figure 16. Locations in the building envelope prone to air tightness problems [71].

In the building envelope, the absence of thermal bridges should be either demonstrated by calculation of thermal bridges across all connections, or by demonstrating thermal-bridge-free-design. Quality assurance of the building envelope should be documented with materials used, working methods, and photographs of work. Next, the quality assurance checks of the insulation layers are performed as the installation tasks are completed. The correct insulation, insulation connection hardware, and connection details must be followed according to the design documents. Also, insulation layers must be uninterrupted and hollow spaces should be avoided [58]. Furthermore, the airtightness of connection details should be checked before they are hidden from easy access. Key airtightness sealing materials in passive houses are vapour permeable butyl tape and vapour permeable hydrophobic expansion foam [70]. When the building envelope is completed, a pressure test should be completed at 50 Pa (n50) with a blower door device with a leak detection indicator.

Figure 17. A Pro Clima brand service grummet sealing a pipe penetration of the airtightness layer [72].

In implementing the execution of a building project for ventilation systems, several quality assurance checks must be performed. In all places where ventilation ductwork penetrates the building envelope, air tightness must be ensured [71]. During the pressure test of the building envelope, the air tightness of all places of penetration should be scrutinized [35]. An example of a pipe penetration sealing grummet is shown in figure 17 above. After the ventilation system is installed and calibrated, a quality assurance check on the whole system must be completed. This initial verification check should measure the supply and extract air flows, adjustment level of balance, adjustment level of supply and extract air distribution in the spaces, and the power consumption of the ventilation system [70].

Lastly, after the completion of installation and calibration work of other building service systems, several quality assurance checks must be performed before moving on to the handover phase [70]. As with the ventilation ductwork, all places where plumbing and electrical installations penetrate the building envelope, air tightness must be ensured around the installation. During the pressure test of the building envelope, the air tightness of all places of penetration should be scrutinized. After the remaining building service systems are installed and calibrated, quality assurance checks of each system must be completed [70]. In these quality assurance checks careful attention must be paid to check energy consumption of systems and thermal insulation of pipes.

7.4 Effective project management of nZEB building projects

The German Passive House Institute's (PHI) Passive House Certification process is a thorough and effective low energy building verification process. PHI has three types of certification criteria which could all three be applied to nZEB project management building, component and designer certification [70]. A building is tested and calculated using the Passive House Planning Package design tool (PHPP) by an organization approved by the PHI. Last, passive house designers can be certified by the PHI. Being certified by the PHI shows that the designer has undergone sufficient training and passed an exam to show understanding of passive house principles [70]. The Passive House certification process begins with certifying the building designer and building designs and then delivering all required documents including the building Energy Performance Certificate (EPC) to the PHI. The required building certificate documents are airtightness certificates, Mechanical Ventilation with Heat Recovery (MVHR) commissioning certificates, conductivity certificates, window schedule and thermal data certificates, and site supervisor declaration certificates [70]. The certification of construction management staff on construction sites would also be very beneficial for nZEBs.

8 Case studies of nZEB office building projects

8.1 Case 1: Etrium Passive House certified office

The façade of the Etrium office building, home of Econcern GmbH Headquarters of Germany, is shown in figure 18 below.

Figure 18. Façade of Etrium nZEB Passive House standard certified office, Cologne, Germany [73].

The Etrium nZEB Passive House standard certified office building is shown in table 9 below.

Table 9. The project data of the Etrium office building [74]

Overview of project data:	
Location:	Cologne, Germany
Building type:	Office building (Net zero primary energy, Passive House certified)
Net floor area:	3751 m^2 (25 m^2/user)
Architect:	Benthem Crouwel Architects, Aachen, NE
Energy concept:	Ecofys Germany GmbH, Cologne
Main contractor:	HIBA Grundbesitz GmbH & Co. KG, Cologne, DE
Environmental assessment consultant:	G. Hoffmann Senior Auditor, Ifies GmbH, DE
Cost:	6.5 million € (1730€/m^2)
Construction duration:	9 months
Completion date:	2008
Innovative feature:	thermal building element activation system for passive heating and cooling
Primary energy consumption (including heating, cooling, electricity, hot water):	116 $kWh/m^2 \cdot a^{-1}$
Heating energy demand:	11 $kWh/m^2 \cdot a^{-1}$
Heat pump:	Capacity of 48 kW, ground water as heat source
Photovoltaic generation:	30,000 kWh / a with 32 kWp (peak)

Project brief

The Etrium building is a three story office building situated in Cologne, Germany. The name of the Etrium building comes from the glazed atrium in the center of the building and the fact that the building is energy efficient. In fact, the Etrium building needs approximately 70% less electricity and about five times less heating energy than a conventional building [74]. The Etrium is a Passive House standard certified building so it has a very low heating demand of only 11 kWh/m^2 per year. The internal heat gains including solar thermal heat gains, equipment and people provide almost all of the necessary heat. The building utilizes a low exergy passive cooling system called Concrete Core Temperature Control (CCTC). The net floor area of the building is 3751m^2 and the net volume is 12480m^3. The Etrium building has received two environmental assessment certifications: the BREEAM Excellent certificate and the seal of quality (golden ‘'Gütesiegel’) of the German Society for Sustainable Building (DGNB). In Germany the golden 'Gütesiegel’ is the highest rating for sustainability.

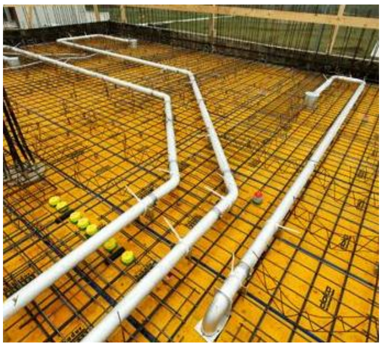


Figure 19. CTC supply air ventilation ductwork before concrete pour (left) [75].

Figure 20. Close-up of CCTC supply air ventilation duct (center) [76].

Figure 21. CCTC network of tube heat exchangers embedded in concrete (right) [76].

HVAC systems

The Etrium building utilizes a passive heating and cooling system (CCTC) which is a low-exergy system, requiring far less primary energy than active cooling systems [76]. In the CCTC system, the supply air ventilation ductwork is partly embedded in the poured in-situ concrete intermediate floor slabs along with a network of tube heat exchangers. The construction phases of this passive cooling system are shown in figures 19-21 above. CCTC is a type of building element activation system, which utilizes the high thermal storage capacity of opaque building elements for heating and cooling. In the Etrium building, water transfers through the network of tube heat exchanger networks embedded in the intermediate floors. As water flows through the tubes, heating or cooling energy is transferred to concrete, thus heating or cooling the structure, as well as the supply air ducts. The thermal mass of the concrete slabs slowly dissipates this stored heating or cooling energy during several hours, 60% through radiation and 40% through convection. [76] The performance of the CCTC cooling system has been successfully proven in other previous buildings in central Europe [76]. An additional benefit of this system is that it does not require underground boreholes as do below-grade borehole heat exchanger systems, which can be expensive and need large amounts of subterranean space [76].

A diagram of the CCTC ventilation air ducts of the Etrium building is shown in figure 22 below. The blue arrows show supply air ducts and the orange arrows show extract air flows; exhaust air ducts are located in the center atrium and restrooms only.

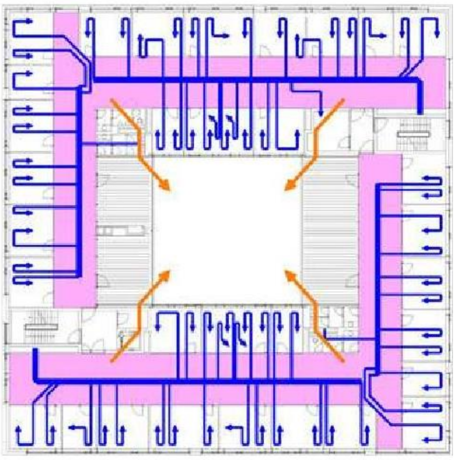


Figure 22. Diagram of the CCTC supply air ventilation ductwork embedded in subfloors [77].

The ventilation system is designed energy efficiently, with as short ventilation ducts as possible. Supply air ducts provide fresh air to 12 individually controlled supply air zones consisting of office and meeting rooms around the center atrium. Air from these zones is extracted in the corners of the main hallways of each floor and from there to the center atrium. The atrium also fulfils a technical function as an exhaust air zone, minimizing the need for extract air ductwork in the surrounding offices. The HVAC system heating and cooling season schematic diagrams are shown in figures 23 and 24 below. The heat of the exhaust air is recovered in the heat recovery unit (HRU) of the ventilation system at 95% efficiency.

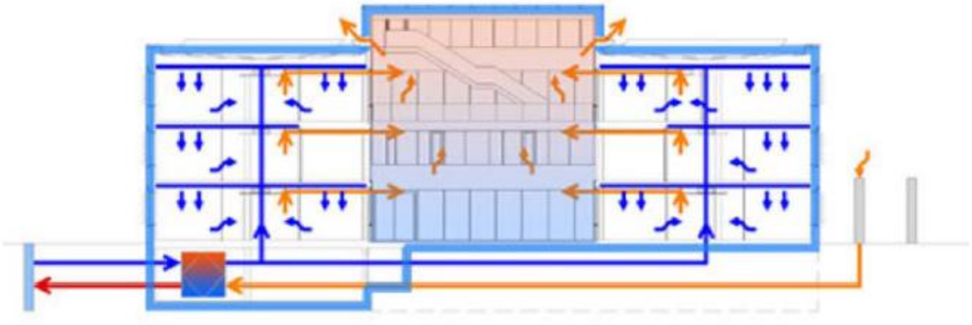


Figure 23. Winter mode of the HVAC systems [77].

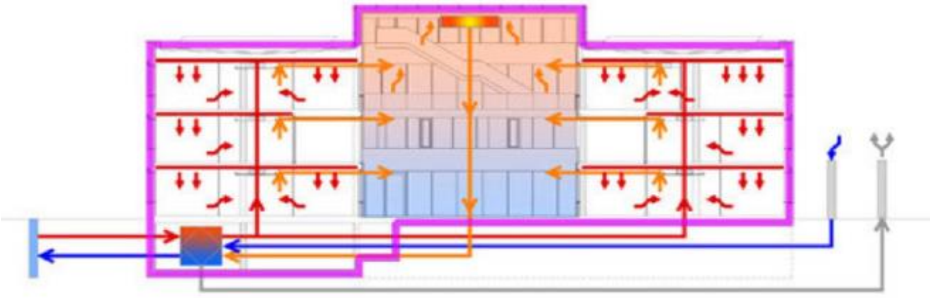


Figure 24. Summer mode of the HVAC systems [77].

The heating balance of the building is small, the heat losses of the ventilation system, the building envelope and very small infiltration rate are largely balanced by the internal heat gains of the building. In turn, the heating demand of this passive house office is only 11 kWh/m^2, saving €1,10/m^2 per month (4126 €/ month) in heating costs compared to an office built to the German building code [74]. The additional space heating demand of the building is met by a ground water heat pump system. The heat pump is very energy efficient and delivers heated air to 12 individually controllable zones. In summer months the ground water heat pump works in reverse as demonstrated in figure 24 above, to cool the fresh supply air. The Etrium building's heating demand for domestic hot water (DHW) is met with two solar thermal collectors on the roof. Also, rainwater is collected on-site and used for grey water for toilets [74].

Renewable energy resources

The Etrium building's energy designer was Ecofys. In the energy design of the Etrium, Ecofys incorporated a great amount of renewable energy generation on-site. Solar thermal energy is collected with the solar thermal hot water system installed on the roof, supplying the DHW heating demand of the building. Additionally, the PV production system installed throughout the roof of the building shown in figure 25 below, generates 30,000 kWh with a 32 kWp peak power output, offsetting much of its low net energy consumption [70]. Also, the Etrium building uses ground water as heat source for its ground source heat pump with capacity of 48 kW. [74]

Figure 25. Roof of the Etrium building with PV panels [74].

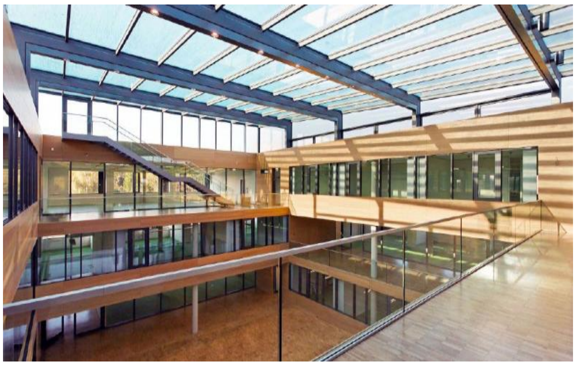


Figure 26. The glazed atrium inside the Etrium building [74].

8.2 Case 2: The Bentley Works redevelopment project

An overview of the Bentley Works redevelopment project is shown in table 10 below.

Table 10. The project data of the Bentley Works project [78.]

Overview of project data:	
Location:	Doncaster, United Kingdom
Building type:	Industrial and office buildings (Net zero primary energy)
Net floor area:	7650 m^2
Developer and main contractor:	Skanska UK
Cost:	40 million £ (5230£ /m^2)
Completion date:	May, 2015
Additional investment in sustainable design:	2 million £ (5% of total costs)
Payback period for extra investment:	6 years
Innovative feature:	First Skanska UK “deep green” project

The Bentley Works Redevelopment project is shown in figures 27 and 28 below.

Figure 27. Completed office building of the Bentley Works facility [78].

Figure 28. 3D site plan of the Bentley Works project [78].

Project brief

The Bentley works brownfield redevelopment project will provide modern office space, upgraded fabrication facilities, and a 5,000 m^2 cutting-edge workshop environment to the Doncaster Skanska office. Skanska will continue to be the tenant after construction. The office building of the Bentley works facility shown in figure 27 above, is home to the management of the Skanska facility. The main function of the facility is for cementation works, namely manufacturing of prefabricated concrete foundation piles [Chris Hayes, Sustainability Operations Director, Skanska, UK, 3 March 2015, personal communication].

Renewable energy resources

The Bentley Works Redevelopment project is a Net Zero Energy Building (NZEB) producing as much energy as it requires for net primary energy consumption annually. The on-site renewable energy is mostly generated from the PV energy production plant, situated on the roof of the 5,000 m^2 manufacturing building. Additionally, to meet the heating peak loads of the building, biofuels are utilized for space heating from the manufacturing plant’s oil waste products. Furthermore, the Bentley Works site has a biomass boiler which uses available biomass produced on-site, from sources such as waste water to generate biogas and electricity [78].

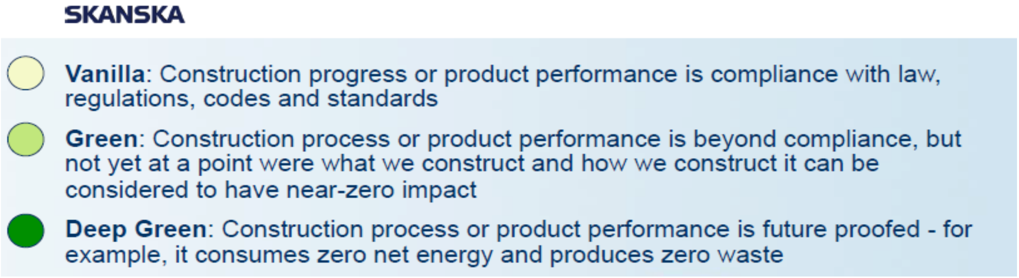
Skanska’s sustainable building framework

Currently Skanska has completed 4 Deep Green construction projects worldwide including an office in Helsingborg, southern Sweden (Väla Gård building), a primary school in the US, and the Skylark 50-50 JV 350 MW onshore wind generation plant in the UK. By the end of 2015 Skanska is aiming to complete 10 new Deep Green construction projects [79]. The premise of Skanska's worldwide sustainability program *The Journey to Deep Green*$^{\mathrm{TM}}$ is, basically, to create buildings that are "future proof" or, in other words, that will meet future legal standards. The six categories of this program, visible on the right side of figure 29 below, for buildings to have a Net Zero (Primary) Energy usage, Near Zero Carbon Construction, Zero Unsustainable Material usage, Zero Hazardous Waste Material usage, Zero Waste (to landfill), and Net Zero Water usage.

Figure 29. The Skanska Color Palette $^{\mathrm{TM}}$ [79].

Skanska has created a Color Palette$^{\mathrm{TM}}$ to help them better describe the environmental impact of construction projects and define the targets of a project. [78]. The Color Palette$^{\mathrm{TM}}$ shown in figure 29 above identifies a Skanska construction project's level of internal green building certifications.

An explanation of the colors of the Color Palette is given in figure 30 below. The colors on the Skanska Color *Palette* ^{TM} range from Vanilla (0) through Green (1), Green (2), Green (3) in the center, to Deep Green (4) on the right.



SKANSKA

Vanilla: Construction progress or product performance is compliance with law, regulations, codes and standards

Green: Construction process or product performance is beyond compliance, but not yet at a point were what we construct and how we construct it can be considered to have near-zero impact

Deep Green: Construction process or product performance is future proofed - for example, it consumes zero net energy and produces zero waste

Figure 30. The definition of the colors of the Color Palette [78].

The Bentley Works Redevelopment project is 100% Deep Green project reaching the highest category of the *The Journey to Deep Green*^{TM} program in all 6 categories of the Color Palette. The site has additionally gained the BREEAM environmental rating system's outstanding level [78].

9 Results and analysis

9.1 Quality assurance tool

The quality assurance tool is presented in Appendix I. The quality assurance tool for nZEB office buildings project package contains two quality assurance tools. The first tool is a quality assurance matrix for the construction stage of nZEB office building projects. The second tool is a set of construction checklists: components or equipment based and system or building assembly based.

The principles of the quality assurance matrix are derived partly from the ASHRAE Commissioning Guide and partly from the lessons learned from the literature review conducted, and the case studies. The quality assurance matrix must be adapted to specific attributes each office building project. In general, the quality assurance matrix shows whom is responsible for verifying the quality requirements of a task and which quality assurance procedure is best suited for each construction task. The matrix has a verification allotment for each construction phase, starting with foundations all the way to the final quality checks just before handover of the building. The types of structures and components of the building to be checked are extensive; from external wall air tightness and thermal performance, to energy management of operational HVAC systems. Effectively, the quality assurance matrix focuses on four important points found in the literature survey thermal performance and air tightness of the building envelope, penetrations of the building envelope, energy management, efficiency of the building service systems (especially HVAC and lighting), correct installation, and efficiency of all on-site RES. The main purpose of the construction checklists is to monitor and enforce that the building owner’s quality and energy performance requirements are being met the main builder and other sub-contractors during construction.

9.2 Results of the literature review

The literature review of this study discussed several central topics of nZEB office buildings and quality assurance. Among the most important principles in nZEBs in section 6.2 were a clear definition, thermal performance and air tightness of the building envelope, energy balance accounting, on-site energy production from renewable energy sources, and load matching.

Additionally, sections 4- 7 addressed several concepts relating to nZEBs including building energy performance metrics, building commissioning, Life Cycle Cost analysis (LCC), passive house buildings, quality assurance of building projects, and low energy building design. Of building energy performance metrics discussed in section 6.2, the three performance indicators (PI) most often used are E-value, net annual delivered energy, and Renewable Energy Ratio (RER). The E-value is the standard PI used to describe a building’s calculated annual net primary energy consumption per net floor area. The net annual delivered energy is the difference of delivered and exported energy, calculated inclusive of primary energy factors for energy carriers.

Building commissioning was found by Mills to lower the risk in building projects and entail median whole building energy savings of 13% [45]. Theory from passive house design is very applicable to nZEBs, since both are types of low energy buildings. Passive houses are buildings which are designed to provide good indoor air quality and thermal comfort solely from heating or cooling of the supply air, without the need to recirculated make-up air. The three types of certification required by the PHI are building, component and designer certification [70]. All three of these certification categories could be beneficially applied to nZEB project management.

From the literature review there are several lessons to be learned from quality assurance principles in construction projects. Considerations of planning quality of a high energy performance building can be divided into four sections planning of the building structure (architectural and structural design), planning of the HVAC systems, planning of the electricity systems, and planning of the energy use of the building [68]. The two main goals of quality assurance in construction projects are: first to strive to produce a product or service after the first attempt which meets the client's quality requirements, and second to verify that the final work produced for each construction phase is completed according to the design documents and by following legal construction regulations and practices. The significance of quality assurance becomes elevated in green building projects with high energy performance targets.

9.3 Results of the case studies

Section 8.1 demonstrated the successful results of the Etrium Passive House Certified nZEB office building. From this building project several lessons may be learned. First, the building project utilized two excellent quality assurance and sustainability tools the Passive House Planning Package (PPHP) and the BREEAM environmental certification system. The PHPP was a requirement for the Etrium to gain Passive House Standard Certification from the PHI. Also, the Etrium project employed a third-party environmental assessment consultant from Ifies GmbH . Utilizing these two quality assurance and sustainability tools allowed this building project reached its ambitious performance and quality goals. Second, the Etrium building demonstrates the energy saving potential of building element activation systems, like the one fused into its HVAC system: Concrete Core Temperature Control (CCTC). Using passive cooling, instead of traditional active cooling, the Etrium building saves a significant €1,10/m^2 per month (4126 €/ month) in cooling costs compared to an office built to the German building code [70]. Since a majority of a building's net energy consumption goes toward meeting its heating and cooling demand, it is wise to focus on minimizing these two energy consuming building services to save the most in annual energy costs.

Section 8.2 demonstrated the results of the brownfield redevelopment project of the Bentley Works facilities. From this second case study several lessons may be learned. First, the building project utilized an excellent internal green building certification program, *The Journey to Deep Green*^{TM}. This sustainable building rating system is used by Skanska to help them better describe the environmental impact of construction projects and define the quality and performance targets of a project. The Bentley Works Redevelopment project is a Net Zero Energy Building (NZEB), producing as much energy as it requires for net primary energy consumption annually. The on-site renewable energy is mostly generated from the PV energy production plant, situated on the roof of the 5,000 m^2 manufacturing building. Additionally, to meet the heating peak loads of the building, biofuels are utilized for space heating from the manufacturing plant's oil waste products.

10 Discussion

The investment of additional time and capital early on in a high energy performance building project shown in section 6.1, has the greatest positive impact on the success of a construction project, especially in meeting the performance goals and all other quality requirements of a building owner [37]. Several previous studies have looked at the planning phase of nZEBs to find design solutions usually aimed at either lowering nZEB energy consumption, lowering nZEB heating or cooling demands, or ways to incorporate renewable energy sources to increase nZEB energy performance. This study examined nZEB and passive house building principles to develop a quality assurance tool applicable to nZEB office building projects.

The premise of this study's main research question presented in section 2.1, was to determine if there is a building energy performance gap in nZEB office buildings. Is there a performance gap between design performance targets and actual measured performance of nearly zero energy office buildings? This study found that there is a performance gap between design performance indicators (PI) such as E-value and net annual delivered energy. This is supported by the study conducted by de Wilde, which demonstrated that there is a general misrepresentation in building energy performance, as it is shown as design energy consumption (expressed as the E-value of a building) in almost all cases.

This study found that passive house building principles are beneficial to apply to nZEB office building projects to minimize the energy performance gap in sections 9.1-2. If and to what extent can quality assurance and design principles from passive house buildings be applied to nearly zero energy office building projects to minimize this performance gap? The passive house building principles which are most valuable in nZEB projects are thermal performance and air tightness of building envelope, EEM in artificial lighting and daylighting, and EEM in HVAC such as heat recovery ventilation and low flow rates of supply air. NZEB building HVAC systems must be designed well and have heat recovery ventilation. The heat recovery rate of the HRU must be as high as cost optimally possible, but at least 85%. The other secondary research question of this study was to analyse the level of quality assurance currently found in high energy performance building projects. Is the level of quality assurance in high energy performance building projects (such as nearly zero energy office buildings) currently as high as it could be? The answer to this research question is not very reliable for two reasons. First, feedback on the quality assurance tool created in this study should be received from some private company knowledgeable in nZEB buildings, or at least low energy building of some kind. Second, the available information on nZEB office building projects in Finland is very limited. This leads one to make the assumption that the level of knowledge in nZEB office building practices is not quite as high in Finland as in other EU countries such as Germany were the Etrium office building examined in case study one is located.

The Etrium office building presented in section 8.1, is an excellent example of a Passive House standard certified office building which has gone the extra mile by reaching the BREEAM outstanding rating and utilized renewable energy sources to make the shift to nearly zero energy. As high energy performance construction starts to produce its initial office buildings, it is predicted that building energy performance will fall short of design net annual energy consumption, resulting in the performance gap discussed in section 4.2. It is predicted that energy performance gaps will be the result of several factors which are not easily foreseeable in building design and energy simulations. These factors include building occupant behaviour, technical short falls in renewable energy production, and possible poor management of buildings by facility management not well versed in the state-of-the-art energy management and building automation systems (BAS).

11 Conclusions

To conclude this study provided many learning opportunities relating quality assurance and design principles of passive house buildings and other theories on low energy building design applicable to nearly zero energy office building projects. One limitation of this study is that it lacked feedback on the quality assurance tool presented in appendix 1 from the construction industry.

Further studies on other nZEB topics will be needed in the future, especially as the Ministry of Environment of Finland will draft a new version of the national building code coming into effect in 2017 and it has declared that all new buildings owned by national government must be passive house buildings by 2016 [80]. The new national building code will include the requirements for nZEBs including threshold value of maximum primary energy consumption and minimum share of on-site renewable energy production for buildings. Additionally, future studies will be required on measuring the actual energy consumption of buildings during the operational phase. Similarly, studies on ways of minimizing the performance gap during the operational phase of buildings through building energy management services, occupant behaviour, responsive building elements, and passive cooling and heating strategies would be beneficial. In a recent article, Kurnitski sums it up nicely, by saying that nearly zero energy building is creating a special demand for buildings which are easy to operate for users, reliable and long-lasting and easy to maintain [81]. This is very true since the nZEB concept includes so many attributes, designers and builders of high energy performance buildings should focus on delivering nZEB building projects which actually perform – as designed and with longevity.

References

1. EC. EU energy in figures - Statistical Pocket Book 2014. Brussels, Belgium: European Commission; 2014.

2. EC. Europe 2020; Europe 2020 in a nutshell; Targets [online]. Brussels, Belgium: EC; 2014.
   URL: http://ec.europa.eu/europe2020/europe-2020-in-a-nutshell/targets/index_en.htm. Accessed: 10 February, 2015.

3. Council of the European Union. Council Directive 2010/31/EU of 19 May 2010 on the energy performance of buildings recast. Official Journal of the European Union, 2010; 53:13-35.

4. Reinikainen, E. Kohti Lähes Nollaenergiarakennusta – FInZEB-hankkeen tulokulmat toimistot. Proceedings FInZEB 2015 results seminar 5 February 2015: Helsinki, Finland [online]. Helsinki, Finland: Granlund Oy.; 2015.
   URL: http://finzeb.fi/wp-content/uploads/2015/02/FInZEB_Reinikainen_Erja_20150205.pdf
   Accessed: 10 February, 2015.

5. Ovando, N., M. Constructive Feedback: A Key to Successful Teaching and Learning. International Journal of Educational Management, 1994, 8(6),9-22.

6. Thomson, K. E. and Wittchen, K. B. European strategies to move towards very low energy buildings, SBI 2008:07. Aalborg, Denmark: Statens Byggeforkingsinstut, Aalborg Universistet; 2008.

7. Ng, B and Akasah, Z. A. Energy Efficient Buildings: An In-depth Look into Definitions, and Design Problems. International Journal of Emerging Sciences, 2013, 3(4),345-358.

8. EC. Low energy buildings in Europe: current state of play, definitions and best practices [online]. Brussels, Belgium: European Commission; 2009.
   URL: http://ec.europa.eu/energy/en/topics/energy-efficiency/buildings.
   Accessed: 10 February, 2015.

9. Council of the European Union. Council Directive 2002/91/EC of 16 December 2002 on the energy performance of buildings. Official Journal of the European Communities, 2003; 1:65-71.

10. EC. Topics: Buildings [online]. Brussels, Belgium: European Commission; 2015.
    URL: http://ec.europa.eu/energy/en/topics/energy-efficiency/buildings.
    Accessed: 10 February, 2015.

11. Hermelink, A. Towards Nearly Zero-Energy Buildings [online]. Berlin, Germany: Ecofys Germany GmbH; 2014. [webinar].
URL: http://www.worldgbc.org/files/2613/9055/9294/
Towards_Nearly_Zero-Energy_Buildings_Ecofys_January_2014.pdf.
Accessed: 24 March 2015.

12. Atanasiu, B., Project coordinator. Principles for nearly zero-energy buildings [online]. Brussels, Belgium: Buildings Performance Institute Europe (BPIE); 2011.
URL: http://www.bpie.eu/documents/BPIE/publications/LR_nZEB%20study.pdf
Accessed: 10 February, 2015.

13. EN 15316-1:2007. Heating Systems in Buildings - Method For Calculation Of System Energy Requirements And System Efficiencies. General. Brussels, Belgium: European Committee for Standardization; 2007.

14. Eike, V., Musall, E. and Lichtme, M. From low-energy to net zero-energy buildings: status and perspectives. Journal of Green Building, 2011,6:1-8.

15. Kurnitski, J. Present situation of nearly zero energy buildings nZEB in Europe [online]. Presentation,Tallin, Estonia: REHVA; 2013.
URL:http://www.ttu.ee/public/e/ehitusteaduskond/Instituudid/
Ehitiste_projekteerimise_instituut/teadus/nZEB/nZEB-situation_in_EU.pdf.
Accessed: 10 February, 2015.

16. Kurnitski, J., Saari, A., Kalamees, T., Vuolle, M., Niemelä, J., and Tark, T. Cost optimal and nearly zero (nZEB) energy performance calculation for residential buildings with REHVA definition for nZEB national implementation. Energy and Buildings, 2011,43:3279-3288.

17. RIL. RIL 265-2014. Uusiutuvien lähienergioiden käyttö rakennuksissa. Helsinki: Finland: Suomen Rakennusinsinöörien Liitto, RIL ry; 2014.

18. Ympäristöministeriö, Sitra ja TEKEs. Era17 – Energiaviisaan rakennetun ympäristön aika 2017 [online] Helsinki, Finland: 2010.
URL: http://era17.fi/ Accessed: 10 February, 2015.

19. García, P. R. European building policies- progress towards the NZEB targets. Proceedings of the European Nearly Zero Energy Buildings Conference 26 February 2015, Wels, Austria.

20. Vehmaskoski, T., editor. Rakennetun omaisuuden tila 2015 [online]. Helsinki, Finland: Suomen Rakennusinsinöörien Liitto RIL; 2015.
URL:www.roti.fi/
document.php?DOC_ID=422&SEC=1d2ddbdb53c1c6336dd2365ccee469e6&SID=1#roti_2015_net_sivut_final_250215.pdf.
Accessed: 10 February, 2015.

21. Suomen virallinen tilasto (SVT): Rakennukset ja kesämökit: Rakennuskanta 2013 [online]. Helsinki, Finland: Tilastokeskus; 2013.
URL: http://tilastokeskus.fi/til/rakke/2013/rakke_2013_2014-05-23_kat_002_fi.html. Accessed: 10 February, 2015.

22. The Ministry of the Environment of Finland. Building energy efficiency (Rakennusten energia-tehokkuus: Määräykset ja ohjeet 2012) D3 Suomen rakentamismääräyskokoelma 2012. Helsinki, Finland; 2011.

23. Ympäristöministeriön asetus rakennksen energiatodistuksesta. Ministry of the Environment of Finland: Helsinki, Finland; 27 February, 2013.

24. de Wilde, P. The gap between predicted and measured energy performance of buildings: A framework for investigation. Automation in Construction, 2014, 41:40-49.

25. EPA. Overview of greenhouse gases [online]. Washington DC, USA: Environmental Protection Agency: 2013.
URL: http://www.epa.gov/climatechange/ghgemissions/gases.html. Accessed: 10 February, 2015.

26. Rodriguez-Ubinas, E., Montero, C., Porteros, M., Vega, S., Navarro, I., Castillo-Cagigal, M., et al. Passive design strategies and performance of Net Energy Plus Houses. Energy And Buildings, 2014,83:10-22.

27. ISO 16818:2008 (E) Building environment design – Energy efficiency – Terminology. Geneva, Switzerland: International Organization for Standardization; 2008.

28. Finnish Meteorological Institute. Climate in Finland [online]. Helsinki, Finland.
URL: http://en.ilmatieteenlaitos.fi/heating-degree-days. Accessed: 10 February, 2015.

29. Schild, P.G., Klinski, M. and Grini, C. Comparison and Analysis of Energy Performance Requirements in Buildings in the Nordic Countries and Europe [online]. SINTEF Byggforsk Project report no. 55, Oslo, Norway 2010.
URL: http://www.sintef.no/globalassets/upload/byggforsk/publikasjoner/sb-prrapp-55.pdf. Accessed: 10 February, 2015.

30. Finnish Meteorological Institute. Heating degree days [online]. Helsinki, Finland.
URL: http://en.ilmatieteenlaitos.fi/heating-degree-days. Accessed: 10 February, 2015.

31. Kohlenbach, P. and Jakob, U. Solar Cooling: The Earthscan Expert Guide to Solar Cooling Systems. Abingdon, Oxon, UK: Routledge/Taylor & Francis; 2014.

32. Salonen, T. FInZEB-kustannuslaskenta: Asuinkerrostalo ja toimisto. Proceedings FInZEB 2015 results seminar 5 February 2015: Helsinki, Finland [online]. Helsinki, Finland: Optiplan Oy.; 2015.
URL: http://finzeb.fi/wp-content/uploads/2015/02/FinZEB_Salonen_Teemu_20150205.pdf
Accessed: 10 February, 2015.

33. Feist,W. Passipedia: The Passive house resource [online]. Darmstadt, Germany: Passive House Institute; 2014.
URL: http://passipedia.org/. Accessed: 10 February, 2015.

34. Paroc Group Oy. Parco Passive House Pilots [online].
URL: http://www.paroc.fi/campaigns/Paroc-Passive-House-Pilots. Accessed: 10 February, 2015.

35. Feist,W. Passive House Planning Package 2013 - version 8 [online]. Darmstadt, Germany: Passive House Institute; 2013.
URL: http://passiv.de/en/04_phpp/04_phpp.htm. Accessed: 10 February, 2015.

36. Barry, R. The Construction of Buildings. Vol.2, 5th Ed. Oxford, UK: Blackwell Science Ltd.; 1999.

37. Paulson, B.C. Designing to Reduce Construction Costs. Journal of the Construction Division, 1976,102(4):587-592.

38. ISO/DIS 15686-5 Buildings and constructed assets – Service life planning. Part 5: Whole life costing. Geneva, Switzerland: International Organization of Standardization; 2004.

39. Sesana, M., M. and Salvalai, G. Overview on life cycle methodologies and economic feasibility for nZEBs. Building and Environment, 2013,67: 211-216.

40. Marszai, A. J. and Heiselberg, P. Life cycle cost of a multi-storey residential Net Zero Building in Denmark. Energy, 2011,36(9):600-609.

41. Gluch, P. and Baumann, H. The life cycle costing (LCC) approach: a conceptual discussion of its usefulness for environmental decision-making. Building and Environment, 2004,39(5): 571-580.

42. Raymond, J. C. & Sterner, E. Reconciling theory and practice of life cycle costing. Building research & Information, 2000, 28;368-375.

43. ASHRAE. ASHRAE Guideline 0-2005: The Commissioning Process; 4 Definitions. Atlanta, Georgia, USA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.; 2005.

44. Friedman, H., Claridge,D., Choinière, D. and Ferretti, N. M., editors. IEA ECBCS Annex 47: Commissioning Cost-Benefit and Persistence of Savings. Varennes, Canada: National Institute of Standards and Technology, and Natural Resources; 2010.

45. Mills, E. Building commissioning: A Golden Opportunity for Reducing Energy Costs and Greenhouse Gas Emissions. [online] Berkeley, CA, USA: Lawrence Berkeley National Laboratory; 2009.
URL: http://cx-lbl.gov/2009-assessment.html. Accessed: 10 February, 2015.

46. Djuric, N. and Novakovic, V. Review of possibilities and necessities of building lifetime commissioning. Renewable and Sustainable Energy Reviews, 2009,13(2):486-492.

47. Mills, E. Building commissioning: a golden opportunity for reducing energy costs and greenhouse gas emissions in the United States. Energy Efficiency, 2011, 4:145-173.

48. Yang, J. R. and Zou, P.X.W. Stakeholder-associated risks and their interactions in complex green building projects: A social network model. Building and Environment, 2014, 73:208-222.

49. Kantola, M. and Saari, A. Commissioning for nearly zero-energy building projects. Construction Innovation, 2014, 14(3):370-382.

50. Holmes, S. Understanding complex credits in LEED certification [online]. Washington, DC, USA: U.S. Green Building Council; 2015.
URL: http://www.usgbc.org/articles/understanding-complex-credits-leed-certification. Accessed: 10 February, 2015.

51. Bointner, R., editor. Affirmative Integrated Energy Design Action: AIDA: D2.1 Best Practice Guide: Operational Success Stories [online]. Vienna, Austria: Vienna University of Technology: Institute of Energy Systems and Electric Drives; 2013.
URL: http://www.aidaproject.eu/downloads/3/AIDA_D21_Success_Stories_EN_small.pdf. Accessed: 10 February, 2015.

52. Andresen, I. Integrated Building Concepts: Actual developments and trends within the IEA; A Workshop within the IEA-ECBCS Annex 44: Integrating Environmentally Responsive Elements in Buildings [online]. Graz, Austria: International Energy Agency; 11 September 2006. [presentation].
URL: http://www.annex44.civil.aau.dk/Annex%2044%20Forum/meetings/5th%20Annex%2044%20Forum/Program_5th%20Annex%20forum.pdf.
Accessed: 10 February, 2015.

53. Heiselberg, P. IEA ECBCS Annex 44: Integrating Environmentally Responsive Elements in Buildings: Project Summary Report [online]. Hertfordshire, UK: AECOM Ltd. for the International Energy Agency; 2012.
URL: http://www.ecbcs.org/docs/ECBCS_Annex_44_PSR.pdf.
Accessed: 10 February, 2015.

54. Pikas, E., Thalfeldt, M. and Kurnitski, J. Cost optimal and neary zero energy building solutions of office buildings. Energy and Buildings, 2014. 74:30-42.

55. Zhu, L., Correia, D. and Boehm, R. Detailed energy savings performance analyses on thermal mass walls demonstrated in a zero energy house. Energy and Buildings, 2009; 41(3):303-310.

56. Mahdavi, A. An introduction to building physics. Vienna, Austria: International Resources Group (IRG) and the Vienna University of Technology; 2010.

57. Wit, M. H. Heat, Air and Moisture in Building Envelopes. Eindhoven, Germany: Technische Universiteit Eindhoven; 2008.

58. Jaggs, M. and Scivyer, C. A Practical Guide to Building Air Tight Dwellings [online]. Amersham, UK: BRE publishing; 2009.
URL: http://www.zerocarbonhub.org/sites/default/files/resources/reports/A_Practical_Guide_to_Building_Air_Tight_Dwellings_NF16.pdf.
Accessed: 15 March, 2015.

59. Künzel, H. M., Zirkelbach, D. and Schafaczek, B. Modelling the Effect of Air Leakage in Hygrothermal Envelope Simulation. Proceedings of the BEST 3 Conference Building Enclosure Science & Technology: Atlanta GA, USA; April 2-4, 2012.

60. Enteria, N and Mizutani, K. The role of the thermally activated desiccant cooling technologies in the issue of energy and environment. Renewable and Sustainable Energy Reviews, 2011; 15(4):2095-2122.

61. Vakiloroya, V., Samali, B., Fakhar, A. and Pishgadam, K. A review of different strategies for HVAC energy saving. Energy Conservation Management, 2014; 77:738-754.

62. Kurnitski, J., editor. Cost Optimal and Nearly Zero Energy Buildings (nZEB): Definitions, Calculation Principles and Case Studies. London, UK: Springer-Verlg; 2013.

63. Salom, J., Widen, J. Candanedo, J., Sartori, I., Voss, K. and Marszal, A. Understanding Net Zero Energy Buildings: Evaluation of Load Matching and Grid Interaction Indicators. Proceedings of Building Simulation 2011: 12th Conference of International Building Performance Simulation Association, Sydney, Australia: 14-16 November 2011.

64. EN 15603:2008. Energy performance of buildings. Overall energy use and definition of energy ratings. Brussels, Belgium: European Committee for Standardization; 2008.

65. ISO-9001:2008 Quality management. Geneva, Switzerland: International Organization for Standardization; 2008.

66. Suominen, E. Rakennusliikkeen laaudunvarmistus. Helsinki, Finland: Rakennusteollisuus RT ry.; 1990.

67. Kankainen, J. Urakoitsijan työmaakansio sopimusasiat. Rakennusurakkaan liittyvät velvollisuudet, vastuut ja oikeudet. Helsinki, Finland: Rakennusteollisuuden Kustannus RTK Oy.;2005.

68. Rakennusteollisuus RT Oy. RT 16-10660: Rakennusurakan Yleiset Sopimusehdot. YSE 1998.

69. RIL. RIL 259-2012 Matalaenergiarakentaminen: Toimitilat. Helsinki: Finland: Suomen Rakennusinsinöörien Liitto, RIL ry; 2012.

70. Feist, W. Quality Approved Passive House Certification: criteria for non-residential passive house buildings [online]. Darmstadt, Germany: Passive House Institute; 2015.
URL: http://www.passiv.de/en/03_certification/02_certification_buildings/02_certification_buildings.htm. Accessed: 10 February, 2015.

71. Carrié, F., Jobert, R. and Leprince, V. Contributed Report 14- Methods and techniques for airtight buildings [online]. Sint-Stevens-Woluwe, Belgium: AIVC;2012.
URL:http://tightvent.eu/wp-content/uploads/2012/04/CETE69_AIVC_Contributed_Report_14.pdf. Accessed: 10 February, 2015.

72. Crosson, N. Airtightness – Part 1 [online]. Bettystown, Ireland: Energyquarter House; 2014.
URL: http://www.energyquarter.com/energy-saving/airtightness/airtightness-part1 Accessed: 10 February, 2015.

73. Benthem Crouwel Architects. Etrium, Cologne [online]. Amsterdam, The Netherlands, 2015.
URL: http://benthemcrouwel.com/?s=etrium#etrium-cologne-1121. Accessed: 10 February, 2015

74. The Competence Atlas Energy NRW. etrium - Largest passive house office in NRW [online]. Düsseldorf, Germany; 2015
URL: http://www.energystate.de/detail.php?lang=en&kat=project&id=152. Accessed: 10 February, 2015.

75. Etze, T. Bürogebäude im Passivhausstandard [online]. Berlin, Germany: Detail magazine; 2009.
URL: http://www.detail.de/architektur/themen/buerogebaeude-im-passivhausstandard-001307.html
Accessed: 10 February, 2015.

76. Lang, J., editor. EnOB: Research for energy-optimized building. Analysis: Concrete core temperature control [online]. Bonn, Germany: FIZ Karlsruhe – Leibniz-Institut für Informationsinfrastruktur GmbH.
URL: http://www.enob.info/en/analysis/analysis/details/concrete-core-temperature-control. Accessed: 10 February, 2015.

77. Architect Science. Towards A New Architecture + Energy - Part 4 [online].
URL: http://www.architectscience.com/images/Towards_A_New_Architecture_Energy_-_Part_4.pdf

78. Hayes, C. The Technicalities of Sustainability. [online]. London, UK: Skanska UK; 2012. [presentation].
URL: http://www.ads.org.uk/download/8031-chris-hayes-skanska. Accessed: 10 February, 2015.

79. Nabholz, T., L. How can the Built Industry Push Sustainability in Practice: A Case Study of Skanska's Color Palette^{TM} [Thesis (M Sc)] [online]. Malmö, Sweden: Malmö University Electronic Publishing; 2012.

URL: http://dspace.mah.se/bitstream/handle/2043/14034/
Tim%20Nabholz%20-%20Masters%20Thesis%20in%20Built%20Environment.pdf?sequence=3&isAllowed=y. Accessed: 24 March 2015.

80. Säteri , J., editor. Rakentamismääräykset uusitaan vuoteen 2017 mennessä [online]. Espoo, Finland: SIY Sisäilmatieto Oy; 2014.
URL: http://www.sisailmauutiset.fi/?p=1824
Accessed: 25 April 2015.

81. Kurnitski, J. Faktat pöytään energiatehokkuuskeskustelussa. Rakennuslehti, No.14, 17.4.2015. Helsinki, Finland: Sanoma Media; 2015

List of figures

Quality assurance for nZEB office building project package

Contents:

1. Quality assurance matrix for the construction phase of nZEB office buildings
2. 3 Construction checklists which are either component based or assembly based

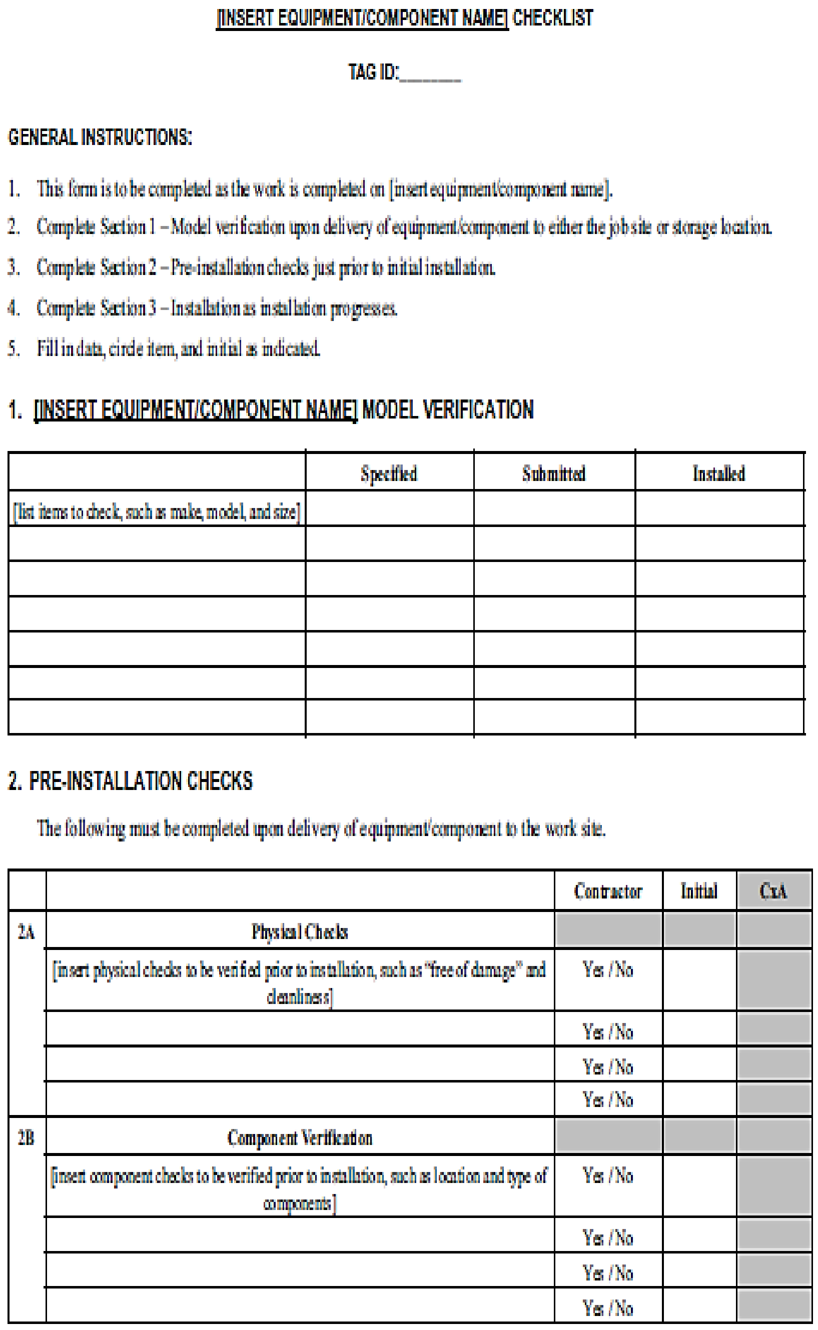
Quality assurance matrix for the construction phase of nZEB office buildings

Task ID:	Structures related	**Quality assurance by construction phase: (down)**	General classification of task	Sub tasks (down)	**Quality Assurance protocols (right)**	Review of design documents	Review of the quality plan related to construction phase/task	Review of construction materials and components	Review of schedule	Review of technical knowledge of laborers	"Tool box meeting" / technical training on-site	Starting meeting of the construction phase or individual task	Inspection of a model installation	Inspection of the first comple working unit	Self handover of work completed	Pre-handover verfication checks of systems	Final inspectio ns
		1. Buidling frame erection															
1.A	Foundation slab (crawl space or slab on grade)		Penetrations through foundation slab	Air tightness and thermal resistivity													
1.B	Foundation slab (crawl space or slab on grade)		Installation of foundation slab	Ensuring technical requirements construction joints													
1.C	Foundation slab (crawl space or slab on grade)		Installation of insulation	Ensuring technical requirements of insulation													
1.D.	Foundation walls		Penetrations through foundation wall	Air tightness and thermal resistivity													
1.E	Foundation walls		Installation of insulation	Ensuring technical requirements of insulation													
1.F	HVAC under foundation slab		Installation of HVAC ducts and components	Ensuring technical requirements of HVAC components													
1.G	1 st floor external walls		Installation of insulation	Ensuring technical requirements of insulation													

Task ID	Structures related	**Quality assurance by construction phase: (down)**	General classification of task	Sub tasks (down)	**Quality Assurance protocols (right)**	Review of design documents	Review of the quality plan related to construction phase/task	Review of construction materials and components	Review of schedule	Review of technical knowledge of laborers	"Tool box meeting" / technical training on-site	Starting meeting of the construction phase or individual task	Inspection of a model installation	Inspection of the first comple working unit	Self handover of work completed	Pre-handover verfication checks of systems	Final inspections
1.G	1 st floor external walls		Installation of insulation	Ensuring technical requirements of insulation													
1.H	1 st floor external walls		Installation of external walls	Ensuring technical requirements construction joints													
1.I	1 st floor external walls		Installation of external walls	Air tightness and thermal resistivity													
1.J	1 st floor external walls		Penetrations through external walls	Air tightness and thermal resistivity													
1.K	1 st floor ceiling intermediate floor elements		Installation of intermediate floor elements or poured in-situ concrete	Ensuring technical requirements construction joints													
1.L	1 st floor ceiling elements outside the external walls (balconies)		Installation of intermediate floor elements or poured in-situ concrete	Air tightness and thermal resistivity													
1.M	2 nd floor external walls		Installation of insulation	Ensuring technical requirements of insulation													
1.N	2 nd floor external walls		Installation of external walls	Ensuring technical requirements construction joints													

Task ID	Structures related	**Quality assurance by construction phase: (down)**	General classification of task	Sub tasks (down)	**Quality Assurance protocols (right)**	Review of design documents	Review of the quality plan related to construction phase/task	Review of construction materials and components	Review of schedule	Review of technical knowledge of laborers	"Tool box meeting" / technical training on-site	Starting meeting of the construction phase or individual task	Inspection of a model installation	Inspection of the first comple working unit	Self handover of work completed	Pre-handover verfication checks of systems	Final inspections
1.R	2nd floor ceiling roof floor elements		Installation of intermediate floor elements or poured in-situ concrete	Ensuring technical requirements construction joints													
1.S	2nd floor ceiling roof floor elements		Installation of intermediate floor elements or poured in-situ concrete	Air tightness and thermal resistivity													
1.T	Roof level external walls (If applicable)		Installation of insulation	Ensuring technical requirements of insulation													
1.U	Roof level external walls (If applicable)		Installation of external walls	Ensuring technical requirements construction joints													
1.V	Roof level external walls (If applicable)		Installation of external walls	Air tightness and thermal resistivity													
1.W	Roof level external walls (If applicable)		Penetrations through external walls	Air tightness and thermal resistivity													
1.Y	Roof structures		Installation of insulation	Ensuring technical requirements of insulation													
1.Z.	Roof structures		Installation of roof structure	Air tightness and thermal resistivity													
1.AA	Roof structures		Installation of roof structure	Ensuring technical requirements construction joints													

Task ID:	Structures related	**Quality assurance by construction phase: (down)**	General classification of task	Sub tasks (down)	**Quality Assurance protocols (right)**	Review of design documents	Review of the quality plan related to construction phase/task	Review of construction materials and components	Review of schedule	Review of technical knowledge of laborers	"Tool box meeting" / technical training on-site	Starting meeting of the construction phase or individual task	Inspection of a model installation	Inspection of the first comple working unit	Self handover of work completed	Pre-handover verfication checks of systems	Final inspections
1.BB	Roof structures		Penetrations through external roof	Air tightness and thermal resistivity													
		2. Exterior doors and fenestrations															
2.A	1 st floor exterior doors and fenestrations		Installation of doors and fenestrations	Ensuring technical requirements construction joints													
2.B	1 st floor exterior doors and fenestrations		Installation of insulation	Air tightness and thermal resistivity													
2.C	2 nd floor exterior doors and fenestrations		Installation of doors and fenestrations	Ensuring technical requirements construction joints													
2.D	2 nd floor exterior doors and fenestrations		Installation of insulation	Air tightness and thermal resistivity													
2.E	3 rd floor exterior doors and fenestrations		Installation of doors and fenestrations	Ensuring technical requirements construction joints													
2.F	3 rd floor exterior doors and fenestrations		Installation of insulation	Air tightness and thermal resistivity													



[INSERT EQUIPMENT/COMPONENT NAME] CHECKLIST

TAG ID:_______

GENERAL INSTRUCTIONS:

1. This form is to be completed as the work is completed on [insert equipment/component name].
2. Complete Section 1 – Model verification upon delivery of equipment/component to either the job site or storage location.
3. Complete Section 2 – Pre-installation checks just prior to initial installation.
4. Complete Section 3 – Installation as installation progresses.
5. Fill in data, circle item, and initial as indicated.

1. [INSERT EQUIPMENT/COMPONENT NAME] MODEL VERIFICATION

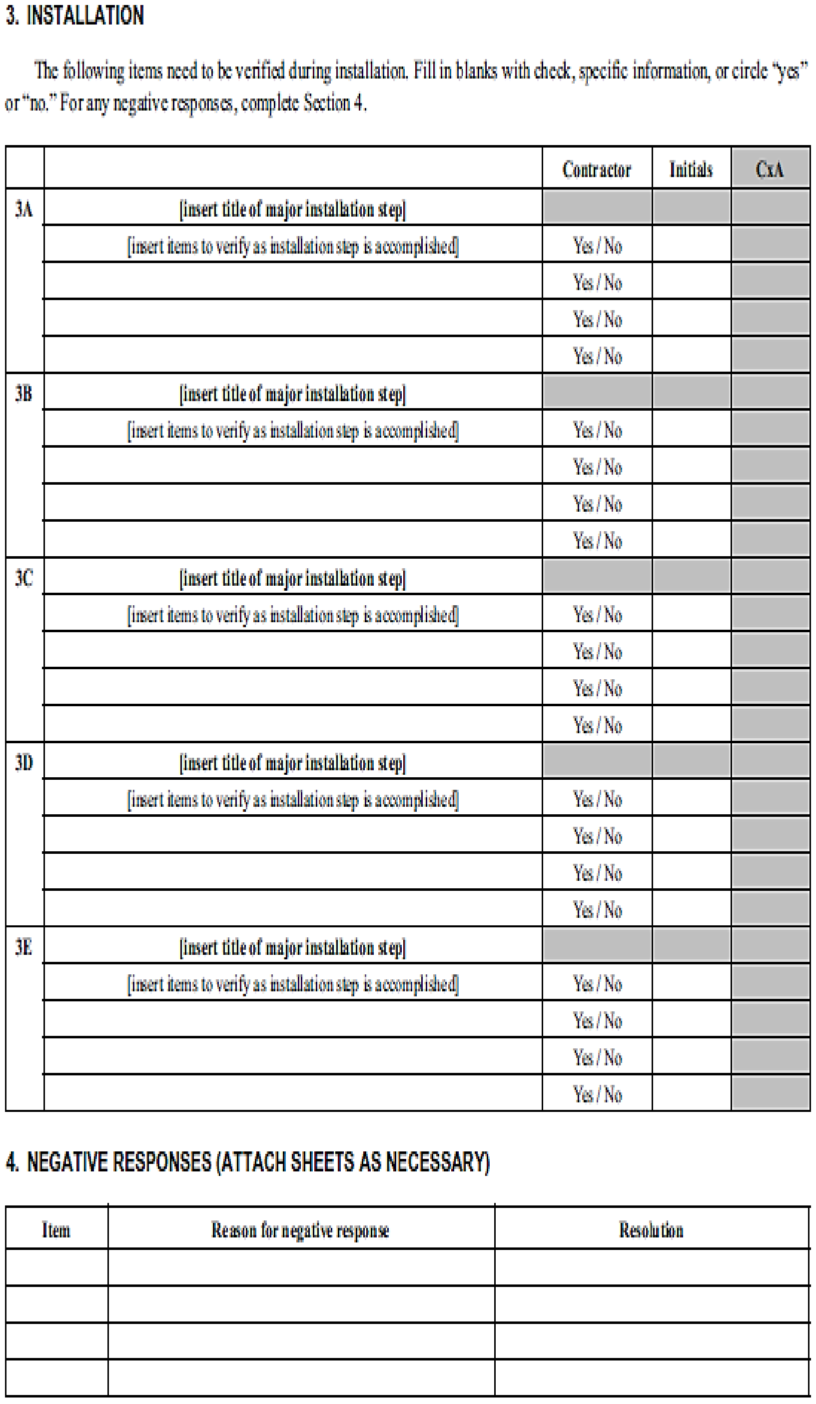
	Specified	Submitted	Installed
[list items to check, such as make, model, and size]			

2. PRE-INSTALLATION CHECKS

The following must be completed upon delivery of equipment/component to the work site.

		Contractor	Initial	CxA
2A	Physical Checks			
	[insert physical checks to be verified prior to installation, such as "free of damage" and cleanliness]	Yes / No		
		Yes / No		
		Yes / No		
		Yes / No		
2B	Component Verification			
	[insert component checks to be verified prior to installation, such as location and type of components]	Yes / No		
		Yes / No		
		Yes / No		
		Yes / No		

Construction checklist 1: Form is from ASHRAE Guideline 0-2005: The Commissioning Process



3. INSTALLATION

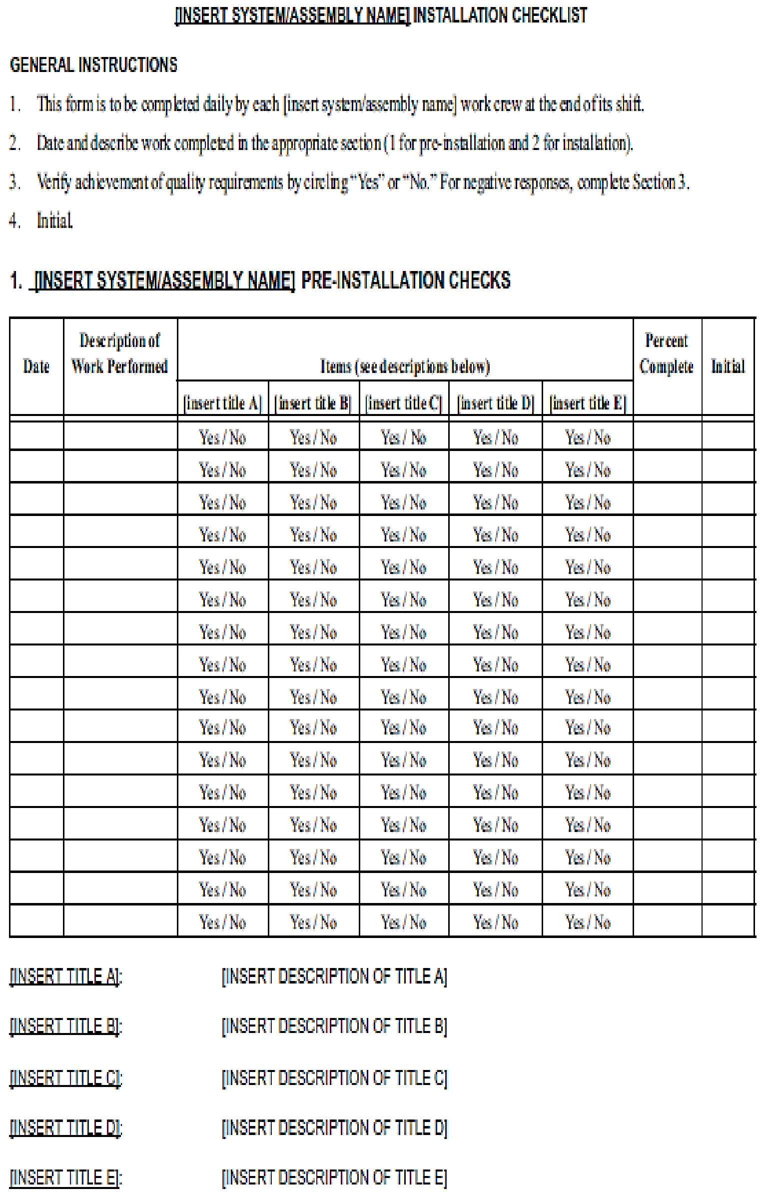
The following items need to be verified during installation. Fill in blanks with check, specific information, or circle "yes" or "no." For any negative responses, complete Section 4.

		Contractor	Initials	CxA
3A	[insert title of major installation step]			
	[insert items to verify as installation step is accomplished]	Yes / No		
		Yes / No		
		Yes / No		
		Yes / No		
3B	[insert title of major installation step]			
	[insert items to verify as installation step is accomplished]	Yes / No		
		Yes / No		
		Yes / No		
		Yes / No		
3C	[insert title of major installation step]			
	[insert items to verify as installation step is accomplished]	Yes / No		
		Yes / No		
		Yes / No		
		Yes / No		
3D	[insert title of major installation step]			
	[insert items to verify as installation step is accomplished]	Yes / No		
		Yes / No		
		Yes / No		
		Yes / No		
3E	[insert title of major installation step]			
	[insert items to verify as installation step is accomplished]	Yes / No		
		Yes / No		
		Yes / No		
		Yes / No		

4. NEGATIVE RESPONSES (ATTACH SHEETS AS NECESSARY)

Item	Reason for negative response	Resolution

Construction checklist 1: Form is from ASHRAE Guideline 0-2005: The Commissioning Process



[INSERT SYSTEM/ASSEMBLY NAME] INSTALLATION CHECKLIST

GENERAL INSTRUCTIONS

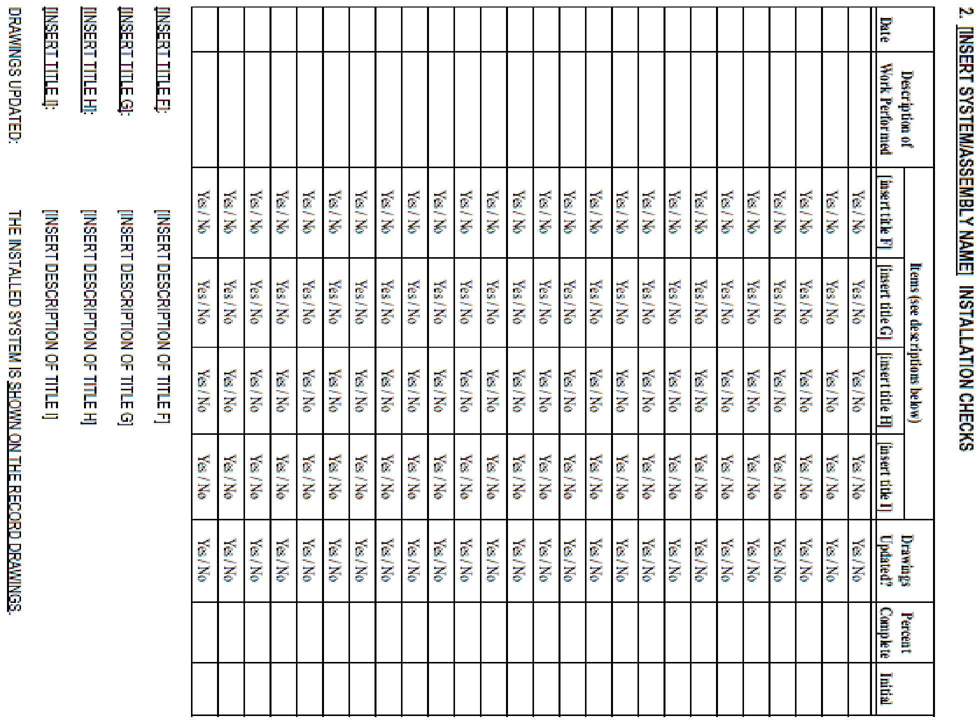
1. This form is to be completed daily by each [insert system/assembly name] work crew at the end of its shift.
2. Date and describe work completed in the appropriate section (1 for pre-installation and 2 for installation).
3. Verify achievement of quality requirements by circling "Yes" or "No." For negative responses, complete Section 3.
4. Initial.

1. [INSERT SYSTEM/ASSEMBLY NAME] PRE-INSTALLATION CHECKS

Date	Description of Work Performed	Items (see descriptions below)					Percent Complete	Initial
		[insert title A]	[insert title B]	[insert title C]	[insert title D]	[insert title E]		
		Yes / No	Yes / No	Yes / No	Yes / No	Yes / No		
		Yes / No	Yes / No	Yes / No	Yes / No	Yes / No		
		Yes / No	Yes / No	Yes / No	Yes / No	Yes / No		
		Yes / No	Yes / No	Yes / No	Yes / No	Yes / No		
		Yes / No	Yes / No	Yes / No	Yes / No	Yes / No		
		Yes / No	Yes / No	Yes / No	Yes / No	Yes / No		
		Yes / No	Yes / No	Yes / No	Yes / No	Yes / No		
		Yes / No	Yes / No	Yes / No	Yes / No	Yes / No		
		Yes / No	Yes / No	Yes / No	Yes / No	Yes / No		
		Yes / No	Yes / No	Yes / No	Yes / No	Yes / No		
		Yes / No	Yes / No	Yes / No	Yes / No	Yes / No		
		Yes / No	Yes / No	Yes / No	Yes / No	Yes / No		
		Yes / No	Yes / No	Yes / No	Yes / No	Yes / No		
		Yes / No	Yes / No	Yes / No	Yes / No	Yes / No		
		Yes / No	Yes / No	Yes / No	Yes / No	Yes / No		
		Yes / No	Yes / No	Yes / No	Yes / No	Yes / No		

[INSERT TITLE A]:	[INSERT DESCRIPTION OF TITLE A]
[INSERT TITLE B]:	[INSERT DESCRIPTION OF TITLE B]
[INSERT TITLE C]:	[INSERT DESCRIPTION OF TITLE C]
[INSERT TITLE D]:	[INSERT DESCRIPTION OF TITLE D]
[INSERT TITLE E]:	[INSERT DESCRIPTION OF TITLE E]

Construction checklist 2: Form is from ASHRAE Guideline 0-2005: The Commissioning Process



2. [INSERT SYSTEM/ASSEMBLY NAME] INSTALLATION CHECKS

Date	Description of Work Performed	Items (see descriptions below)				Drawings Updated?	Percent Complete	Initial
		[insert title F]	[insert title G]	[insert title H]	[insert title I]			
		Yes / No	Yes / No	Yes / No	Yes / No	Yes / No		
		Yes / No	Yes / No	Yes / No	Yes / No	Yes / No		
		Yes / No	Yes / No	Yes / No	Yes / No	Yes / No		
		Yes / No	Yes / No	Yes / No	Yes / No	Yes / No		
		Yes / No	Yes / No	Yes / No	Yes / No	Yes / No		
		Yes / No	Yes / No	Yes / No	Yes / No	Yes / No		
		Yes / No	Yes / No	Yes / No	Yes / No	Yes / No		
		Yes / No	Yes / No	Yes / No	Yes / No	Yes / No		
		Yes / No	Yes / No	Yes / No	Yes / No	Yes / No		
		Yes / No	Yes / No	Yes / No	Yes / No	Yes / No		
		Yes / No	Yes / No	Yes / No	Yes / No	Yes / No		
		Yes / No	Yes / No	Yes / No	Yes / No	Yes / No		
		Yes / No	Yes / No	Yes / No	Yes / No	Yes / No		
		Yes / No	Yes / No	Yes / No	Yes / No	Yes / No		
		Yes / No	Yes / No	Yes / No	Yes / No	Yes / No		
		Yes / No	Yes / No	Yes / No	Yes / No	Yes / No		
		Yes / No	Yes / No	Yes / No	Yes / No	Yes / No		
		Yes / No	Yes / No	Yes / No	Yes / No	Yes / No		
		Yes / No	Yes / No	Yes / No	Yes / No	Yes / No		
		Yes / No	Yes / No	Yes / No	Yes / No	Yes / No		
		Yes / No	Yes / No	Yes / No	Yes / No	Yes / No		
		Yes / No	Yes / No	Yes / No	Yes / No	Yes / No		
		Yes / No	Yes / No	Yes / No	Yes / No	Yes / No		
		Yes / No	Yes / No	Yes / No	Yes / No	Yes / No		
		Yes / No	Yes / No	Yes / No	Yes / No	Yes / No		
		Yes / No	Yes / No	Yes / No	Yes / No	Yes / No		

[INSERT TITLE F]:	[INSERT DESCRIPTION OF TITLE F]
[INSERT TITLE G]:	[INSERT DESCRIPTION OF TITLE G]
[INSERT TITLE H]:	[INSERT DESCRIPTION OF TITLE H]
[INSERT TITLE I]:	[INSERT DESCRIPTION OF TITLE I]
DRAWINGS UPDATED:	THE INSTALLED SYSTEM IS SHOWN ON THE RECORD DRAWINGS.

Construction checklist 3: Form is from ASHRAE Guideline 0-2005: The Commissioning Process

3. CONFLICTS (ATTACH SHEETS AS NECESSARY)

Date	Description of Conflict	Suggested Resolution	Resolved?
			Yes / No
			Yes / No
			Yes / No
			Yes / No
			Yes / No
			Yes / No
			Yes / No
			Yes / No
			Yes / No
			Yes / No
			Yes / No
			Yes / No
			Yes / No
			Yes / No

Construction checklist 4: Form is from ASHRAE Guideline 0-2005: The Commissioning Process