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A model for cost-optimal simulation of new Nearly Zero Energy Buildings (NZEBs) in Europe

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Contents

Abstract

The recast of the Directive on Energy Performance of Buildings (EPBD) states that new buildings occupied and owned by public authorities have to be nearly zero energy buildings (NZEBs) after December 31, 2018 and that all new buildings have to be NZEBs by December 31, 2020. The Directive also requires Member States to establish minimum energy performance requirements leading to the lowest building costs. Reaching buildings requiring nearly zero energy at the lowest cost is still an open challenge through Europe.

This report presents a novel model for the simulation of cost-optimal choices of energy efficient measures for new buildings. The model is applied to evaluate the feasibility of EU requirements for new NZEBs constructions located in different European cities. The model combines energy simulation and cost optimization. It performs hourly sequential simulations over a year showing how to best achieve a nearly zero energy design at the lowest cost in 14 locations across Europe. The model is applied to a new residential building prototype, taking into consideration local hourly climatic data, relevant construction methods, cost data and energy consumption. A novelty is the inclusion of the possible impact of climate change on the estimated cooling loads.

A key finding of the research is that a source energy reduction of 90% and beyond is feasible for new constructions in all selected locations. Results highlight how the cost-optimal measures vary with climate and how in each location final costs are different. They also confirm the importance of both renewables and energy efficiency measures to reach the NZEBs target.

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1 Introduction

Residential and commercial buildings are globally estimated to consume approximately 40% of primary energy and to be responsible for 36% of greenhouse emissions in Europe [1]. The European Union promulgates specific policies to reduce energy consumption in buildings. The Energy Performance of Buildings (EPBD) Directive, together with the Energy Efficiency Directive (EED) (EU, 2012/27/EU) and the Renewable Energy Directive (RED) (EU, 2009/28/EU), set out a package of measures to create the conditions for significant and long term improvements in the energy performance of the Europe's building stock [2][3][4][5].

The EPBD recast introduces the concept of nearly zero energy building (NZEBs). It has been defined as a building that "has a very high energy performance with a low amount of energy required covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby". Article 9 states that Member States shall ensure that new buildings occupied by public authorities and properties are Nearly Zero Energy Buildings (NZEBs) by December 31, 2018 and that all new buildings are NZEBs by December 31, 2020. Furthermore, the Directive establishes the assessment of cost-optimal levels related to minimum energy performance requirements in buildings. The assessment of cost optimality and high performance technical solutions underpins the deployment of NZEBs. Therefore, the importance of integrating the NZEBs concept into National Building Codes and International Standards is widely recognized [6].

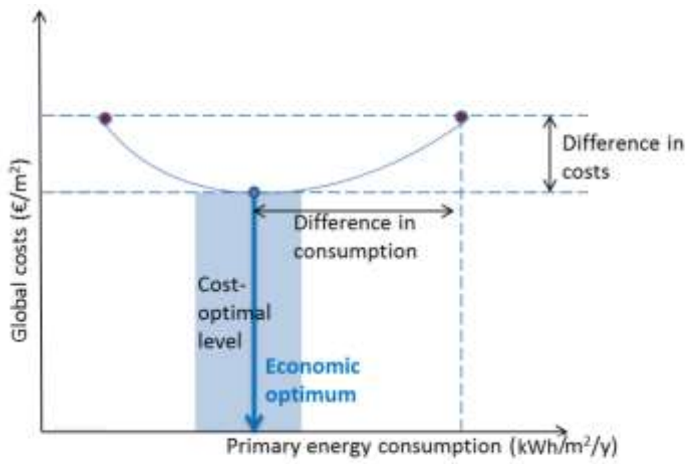
Member States have to define what a NZEB is within their national framework. Other open issues concern how to combine NZEBs requirements with the need to optimize the investments involved and the associated reduction in energy costs, and how to carry out performance level calculations in each country [7].

Nearly, net or positive energy buildings have been constructed and monitored in various projects in Europe. However, the trade-off between the cost of incremental measures and higher performing appliances and renewable energy generation has not been completely addressed.

In relation to cost-optimality, the EPBD requires Member States to evaluate minimum energy performance requirements leading to the lowest building costs. The Directive introduces a methodology to set benchmark requirements for national standards. The cost-optimal level is defined as “the energy performance level which leads to the lowest cost during the estimated economic lifecycle”. According to Article 5, energy-related investment costs, maintenance, operating costs and, where applicable, disposal and replacements costs, have to be considered in the analysis. Delegated Regulation No. 244/2012 and its Guidelines describe the methodology to be followed by Member States to derive cost-effectiveness from a technical and economic perspective [8][9]. The methodological framework comprises both new and existing buildings undergoing major and non-major renovation of their structural and technical components.

According to the methodology, construction alternatives have to be included and compared in terms of costs [10] and energy performance [11] among the available solutions. The optimal configuration presents the lowest costs maintaining a high performance. It can be identified in the lower part of the curve that reports global costs (€/m^2) vs energy consumption (kWh/m^{2}y) (Figure 1).

Figure 1. The cost-optimal solution.



Source: JRC, 2023.

Different studies have shown that several parameters can alter the shape of the curve, among them geometrical building features, technical systems, energy prices, discount rates, and costs [12][13][14][15][16]. A sensitivity analysis can be performed to understand and reduce this variability within calculations. In the implementation of a cost-optimal approach, Member States have to decide on many important aspects, such as the choice of reference buildings, the selection of packages of energy efficient measures, reference construction and maintenance costs of building elements, reference lifetime of building elements, discount rates, and energy prices.

A heterogeneous situation characterizes European countries as each building and climate types present a different cost-optimal level of energy efficient measures [17]. A broad overview on the implementation of the cost-optimal methodology in Member States has been published by BPIE (Buildings Performance Institute Europe) [18]. The study reports calculation examples for Austria, Germany and Poland as well as the impact of discount rates, simulation variants, costs and energy prices on the final results.

The present report illustrates the development of a model for a cost and energy optimization of NZEBs residential constructions in European locations. The model is based on the software BEopt for the implementation of energy simulations and cost optimization.

Under the energy point of view, NZEBs has been performed using the software EnergyPlus. NZEBs have to combine efficiency, thermal improvement measures and renewable production. The applied methodology is aimed at identifying the lowest cost path to reach the NZEB target, which is defined as a buildings saving 90% of source energy for all end uses in reference to a fixed baseline case.

Both building thermal performance and appliances' efficiency system efficiencies are taken into account in the analysis. Renewable energy electricity production from a potential rooftop solar photovoltaic system is directly compared to the cost of energy savings by efficient technologies and construction methods. A cost database and a library of potential measures have been established and used for the cost-optimization approach. Costs of competing components along with their life expectancy and replacement costs have been included in the model. A thermal analysis has been performed to derive space heating, space cooling and water heating consumption in all locations using hourly weather data. Results are compared to varying construction techniques, materials, equipment, energy costs, and other performance parameters variations for sensitivity analysis. Results allow the identification of the most suitable cost-effective method to reach NZEBs in different locations. Results, computed in parallel for all competing options, allow the identification of the most suitable cost-effective method to reach NZEBs in different locations.

2 Building Modelling

BEopt is an energy simulation software, developed by the U.S. National Renewable Energy Laboratory, able to include an economic evaluation in the optimization model. It is possible to evaluate both new and existing building design and to consider how component properties influence the optimal choices for house retrofits. The calculation model in BEopt uses the hourly energy simulation EnergyPlus developed by the Lawrence Berkeley National Laboratory and the U.S. Department of Energy [19].

The model estimates hourly household heating, cooling, water heating and appliance loads within EnergyPlus. Fundamental building thermodynamics are estimated via finite difference conduction functions based on a multi-zone representation that allows a robust evaluation of transient thermal phenomena. A variety of energy carriers can be simulated. The results of the simulations have been compared to real buildings with measured data to verify its potential to replicate measured energy use both in cold and in hot climates [20]. In this study, the outputs of the baseline energy simulations have been compared with typical site energy consumption across European climates [18].

The simulation model has been adapted to run in European climates by adding hourly International Weather for Energy Calculations (IWEC) weather data files [21], by converting to metric inputs and by adapting costs data to the European values. Using similar inputs, comparisons have also been produced relative to predicted energy use and measure savings against the Passivhaus Planning Package (PHPP) software [22]. Solar thermal and solar photovoltaic (PV) system output is also evaluated. The economic optimization method applied in the model is consistent with established procedures for NZEBs cost-optimality.

To enable the cost-optimal methodology, a library of energy efficient measures has been defined with their characteristics as well as their specific costs, life expectancy, operation, maintenance, and replacement costs. The renewable energy production is evaluated using a photovoltaic (PV) simulation tool (transient simulation program: TRNSYS) [23]. This simulation also predicts solar water heating performance relative to domestic hot water heating needs. For a given location, this allows to directly the cost effectiveness of energy efficiency measures as compared with the cost of renewable energy production to determine the most convenient path to nearly zero energy buildings. Even in cold climates, this method offers some advantages compared to the standard Passivhaus approach, as it shows that it is possible to reach zero energy performance at a lower cost [24].

The optimization model evaluates the entire suite of energy efficient options and selects the option with the highest net present value savings, balancing investment (considering both costs against energy and savings). It incorporates this option in the reference building, and then the simulation is run again to identify the next best option with highest present value savings. The process continues iteratively until the source energy savings are reached or until zero energy is achieved using renewables.

2.1 Energy and economic optimization

The optimization process is designed to find, starting from the baseline building, the most cost-effective set of energy efficiency measures mainly related to the building envelope, domestic appliances, and building systems. These measures are evaluated against the cost of electricity and natural gas bought from the utility, and taking into account the cost of producing solar electricity using roof-top photovoltaics.

The software contains a library of approximately 150 energy efficiency options. The optimization method sequentially searches for the most cost-effective option across a range of categories (walls, floor and ceiling insulation levels, window glass type, HVAC type, etc.) to identify the optimal building design able to reach the target performance at the lowest cost.

The energy use of the baseline building is evaluated using EnergyPlus and TRNSYS. All the options are then compared to the baseline building in a long series of parametric evaluations with energy saving results calculated and stored for each measure implemented.

ESavings_i,n = (Base_energy, n – Measure_energy, n,i)

Where:

ESaving n,i = Energy savings within optimization iteration ‘n’ evaluated for option ‘i’

Base_energy, n = Calculated energy use of the baseline building at the beginning of iteration ‘n’

Measure_energy, n,i = Estimated energy use of the base building with measure ‘i’ installed within iteration ‘n’

The cost effectiveness for each option is derived by estimating the net present value (NPV) of the cost of the improvement or change over the life of the building. This is compared with the cost of the changing baseline building through the optimization process.

NPV n, i= I (Vn, an)

$$\mathrm{PV} = I\,(V_n a^n) + \sum_{j=1}^{n} a^j \left(M_j + R_j\right) + \sum_{k=1}^{H} \sum_{j=1}^{n} P_k\, Q_k\, b^j$$

Where:

PV = total present-value of life-cycle costs before taxes, associated with a given energy system

I = total first costs associated with energy saving measure, including purchase, installation, building modification, and improvement

Vn = residual or salvage value at year n, the last year in the evaluation (50 years)

a = single-present-value formula computed for a designated year from j = 1 to n, and discount rate d; i.e. aj = (1 + d)-j

Mj = maintenance costs in year j

Rj = repair and replacement costs in year j

Pk = the initial price of the kth type of conventional energy carrier for energy types k = 1 to H

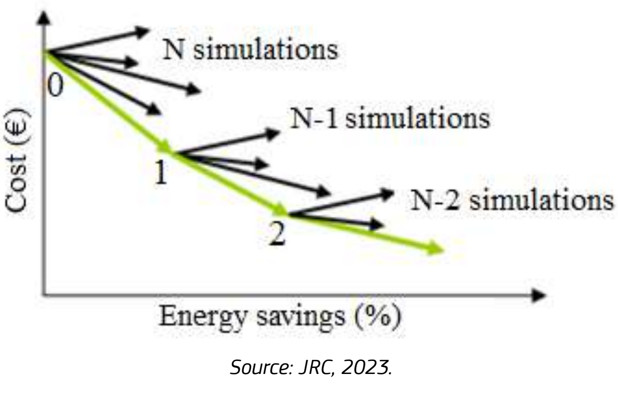
Qk = the quantity required of the kth type of energy

b^j = a formula for finding the present value of an amount in the jth year, escalated at a rate ⍰k, where k denotes the kth type of energy carrier, and discounted at a rate d; i.e. b^j = $[(1 + \Theta_k)/(1 + d)]$

Each option, in each iteration, has a calculated NPV or the combination cost of the purchase and ownership of the measure as well as the costs for energy needs associated with the measure. The total costs over the life of the analysis are then annualized to a yearly cost of energy and additional mortgage expenses associated with the added incremental costs of that measure.

At each iteration, the single most cost-effective option (lowest annualized cost of investment and energy costs) is selected after having evaluated all the measures. Within the optimization process, the baseline building evolves and it is modified by adding the selected option at the end of an iteration and before proceeding to the next. All remaining options are then re-evaluated together with the next selected option as illustrated in Figure 2. This process continues until the performance target is reached or the available cost-effective options are exhausted.

Figure 2. Illustration of the sequential search process to reach the NZEB target.



Source: JRC, 2023.

The sequential search technique has a number of advantages. Not only does it attempt to reach the established target, but it locates the least expensive path to achieve that target. It further locates intermediate optimal points along the path, i.e. minimum-cost building design at different energy savings levels. Thus, it is possible to identify what the 50% reduction level is along the path to reach a NZEB target.

Another advantage is that single building options are evaluated, reflecting realistic construction options. This means that specific materials, equipment and appliances can be evaluated given realistic features of available products. Finally, near-optimal alternative designs are also identified within the optimization process. This is important since many competing solutions may be very close to the specifically located optimum. Furthermore, sometimes costs may be uncertain or variable for some options. In addition to simply searching for the sequence of optimal improvements in a building design, the model also evaluates special cases with negative interactions. It can simulate: 1) removing previously selected options, such as changing fuels when loads have become very low; 2) re-evaluating previously rejected combinations of options. Specific combinations of options can be evaluated together in order to isolate potential synergistic effects.

2.2 Economic Parameters

In all locations, many measures have been selected from available energy conservation measures (ECMs). The simulated energy demand from each energy carrier together with cost data are used to analyse the cost effectiveness of individual measures.

Cost effectiveness calculations are based on the present value of life-cycle costs considering projections over an analysis period of 30 years. The procedure for estimating life-cycle cost calculations are well documented [25]. The assumed economic parameters are shown in Table 1.

Table 1. Economic parameters for the optimization.

Category	**Rate**
General Inflation Rate (GR)	2.0%
Energy Price Inflation Rate (ER)	3.0%
Financing Interest Rate (MR)	5.0%
Discount Rate (DR)	5.0%
Down Payment with Financing	10.0%

They are based on recommended guidelines supplementing Directive 2010/31/EU. The considered electricity price in Milan is € 0.25/kWh while the current natural gas price is €10/ GJ or €0.058 kWh gas. In order for the results to not be dominated by regional differences in energy costs, a weighted EU average has been assumed. The assumed costs, service lives, and maintenance fractions for each of the hundreds of efficiency measures considered are given in an Excel sheet linked to the simulation. The value of the energy price inflation rate implicitly approximates the EU Emissions Trading Scheme with carbon pricing assumptions of 25€/tCO2 in 2020 to 39€/tCO2 in 2020. Although the selected rates are based on the EC guidance, a sensitivity analysis has been performed for the Milan optimization case, given current prevailing conditions which suggest lower inflation and financing rates. The new parameters for the sensitivity analysis are: General Inflation Rate (GR) 1.0%, Energy Price Inflation Rate (ER) 0.5%, Financing Interest Rate (MR) 4.0%, Discount Rate (DR) 4.0% [26].

It is possible to alter the input parameters to consider very long time horizons and/or higher energy inflation rates. The optimization can also be limited to non-equipment options, providing a better evaluation of one-time interventions, such as those related to envelope insulation.

Energy costs for electricity and natural gas are taken from [1]. No financial incentives have been assumed for either efficiency or renewable energy sources. However, a differing lifetime is specified for each measure considering data from a number of sources, including Standard EN-15459. For instance, most insulation measures are assumed to last at least 50 years as opposed to renewable energy systems. These systems might last 20-30 years and require operation and maintenance during that time as well as replacement before the end of the analysis period. A key point in the analysis is that if a PV electricity system is specified, its cost-effectiveness becomes the key economic test for other competing measures, which should be installed before the PV system is considered. However, in this analysis, based on solar system performance (which depends on location weather data), and cost competitiveness with efficiency options, the PV system is often been installed midway through the optimization process with further efficiency measures then added as needed at the end to achieve the NZEB target.

2.3 Geographic locations

The optimization of both building energy efficiency and solar power production requires incorporating specific data on climate severity and solar irradiance in a location. Appliance efficiency also plays a part in this optimization since improved appliance efficiency alters building internal heat generation rates and the resulting heating and cooling needs. However, the relative need for heating and cooling is also of importance in that location as a function of its climate. In order to highlight efficiency and renewable potentials due to location and prevailing climate, a consistent series of measure costs were used to evaluating the performance of the various options.

For the analysis, locations across Europe have been selected in order to have at least one representative city in the different climates. Given the very large degree of climatic variation, 14 locations have been considered (Table 2). These data came from the IWEC hourly weather data that are then used by EnergyPlus simulation to predict heating and cooling needs, and by TRNSYS to predict how solar power production varies over time. The selected locations for the modelling of the reference building are listed in Table 2.

Table 2. Modelled locations.

Location name	Country
Amsterdam	Netherlands (NL)
Athens	Greece (EL)
Berlin	Germany (DE)
Bucharest	Romania(RO)
Dublin	Ireland (IE)
Larnaca	Cyprus (CY)
Lisbon	Portugal (PT)
Madrid	Spain (ES)
Milan	Italy (IT)
Paris	France (FR)
Rome	Italy (IT)
Stockholm	Sweden (SE)
Vienna	Austria (AT)
Warsaw	Poland (PL)

Source: JRC, 2023.

The IWEC hourly weather data has been processed for each location to calculate Heating Degree Days (HDD) and Cooling Degree Days (CDD) derived from heating degree hours (HDH) and cooling degree hours (CDH) respectively using the following formulae:

$$\mathrm{CHH} = \mathrm{T} - 18.5$$

$$\mathrm{HDH} = 18.5 - \mathrm{T}$$

if CDH <0 then CDH = 0, if HDH <0 then HDH = 0

where: T= hourly air temperature as obtained from EnergyPlus

$$\mathrm{CDD} = \frac{\sum_{1}^{8760} \mathrm{CDH}}{24}$$

$$\mathrm{HDD} = \frac{\sum_{1}^{8760} \mathrm{HDH}}{24}$$

Error! Reference source not found. reports the main climatic data for the simulated locations.

Table 3. Minimum, maximum temperature, heating and cooling degree days, and daily average solar irradiance in the simulated locations.

Location	Minimum temperature (°C)	Maximum temperature (°C)	Cooling Degree Days (d)	Heating Degree Days (d)	Daily average global solar irradiance ($kWh/m^2/d$)
Amsterdam	-8.4	32.7	92	3185	2.69
Athens	2.0	37.2	1035	1254	4.57
Berlin	-9.1	32.8	204	3372	2.70
Bucharest	-20.0	38.8	492	3305	3.81
Dublin	-4.2	24.2	15	3185	2.59
Larnaca	1.0	36.5	1221	904	5.13
Lisbon	4.1	36.0	558	1353	4.52
Madrid	-4.6	40.4	703	2222	4.30
Milan	-11.2	33.0	366	3048	2.93
Paris	-6.0	30.0	204	2889	2.93
Rome	-4.0	31.8	640	1618	4.01

Location	Minimum temperature (°C)	Maximum temperature (°C)	Cooling Degree Days (d)	Heating Degree Days (d)	Daily average global solar irradiance (kWh/m^2/d)
Stockholm	-17.0	27.1	75	4460	2.53
Vienna	-18.3	31.7	265	3382	3.08
Warsaw	-16.0	32.0	160	3856	2.74

Source: JRC, 2023.

2.4 The building prototype

The methodology is now illustrated for Milan (Italy). A standard new house of 120 m2 above grade with a full cellar has been considered. This building is similar to prototype described in a recent study by Ecofys GmbH and the Danish Building Research Institute [27] with some additional details on lighting and appliances as required in the Beopt simulation. Its main characteristics are summarized in Table 4. The same table reports system properties, insulation levels, airtight equipment efficiencies and appliances. This building represents a standard energy performance starting point for the optimization process of this research.

As a baseline for lighting, it was assumed that 80% of the lighting devices were equipped with incandescent bulbs, even though lighting is currently in a state of rapid change in EU. It must be noted, however, that the lighting segment is so cost-effective that even assuming a 30% saturation of incandescent lighting systems, the change to compact fluorescent lights (CFL) or light emitting diode (LED) devices would still be among the first measures chosen in the optimization process.

It is important for the analysis that both a heating and cooling system are potentially available in all climates. Some measures, such as window solar heat gain selection, will involve a trade-off between the balance of heating and cooling. Similarly, mechanical ventilation is seen as desirable across climates even in the baseline configuration for adequate indoor air quality.

Table 4. Characteristics of the baseline building used in the optimization.

House Size	120 m^2 over 2.5 m cellar containing heating equipment
Neighbors	Similar neighboring buildings on the two sides of the house
Envelope	
Windows	23 m^2 with double clear glass (~2.2 W/m^{2}K)
Walls	R 1.3 Insulated perlite filled masonry walls (~0.8 W/m^{2}K)
Attic	R-5.3 insulation (~0.18 W/m^{2}K)
Doors	Insulated wood entry door (~0.8 W/m^{2}K)
Air Leakage	Standard construction (4 ACH at 50Pa blower door pressure)
System	
Heating	Hydronic natural gas heating system, 82% efficiency
Cooling	COP 4.1 mini-split cooling system

T Set point	20ºC for heating, cooling23ºC
Hot Water	155 l insulated boiler in cellar providing 120 l per day at 55ºC
Mechanical Ventilation	20.3 1/s continuous with 72% efficient ERV

Source: JRC, 2023.

Table 5 reports the characteristics of the baseline building and the optimized choices for building appliances and renewables after the simulation iterations.

Table 5. Baseline and optimized building characteristics for appliances and renewables.

	Baseline	**Optimized**
Appliances	A+	Option A+++
Refrigerator	340 kWh/yr	201
Cooking	334 kWh/yr	302 (Induction)
Dishwasher	319 kWh/yr	258
Clothes dryer	0.98 kWh/kg	0.59 kWh/kg
Clothes washer	183 KWh/yr	150 kWh
Lighting	80% incandescent:600 kWh/yr	100% CFL/LED: 175 kWh/yr
Renewables		
PV System	None	4.0 kWp with 95% efficient inverter
Solar Hot Water	None	6m² closed-loop system

Source: JRC, 2023.

A water heating load of 120 l/day has been considered. The size of the potential PV system (4.0 kWp) has been chosen based on the available South facing roof area (72 m²), selecting efficient modules and allowing the possibility for installing a 6m2 solar water heating system.

According to [28], the temperature in Europe is likely to increase in the near future. Considering that the simulated new building would be used for decades, we consider adjustments to the simulation assumptions to account for this change. Typically, for evaluating the cooling loads in residential buildings, a thermostat cooling set-point of approximately 25 °C is assumed identical to that selected for analysis by the Danish building institute [18]. To compensate for higher cooling loads in the future due to climate change, a set-point of 23 °C has been adopted. This change is in line with recent climate change predictions, but it is still a measure that provides an indication of the importance of addressing cooling loads in future buildings in European housing stock. This accounts for the likelihood that cooling loads could grow over Europe with warmer temperatures.

A mini-split cooling system has been included as available in the optimization analysis in the prototype building of all locations. This has the important advantage of carefully considering options that might reduce heating, but adversely impact cooling loads. The exclusion of a cooling system would have favored options that may lead to overheating. This is particularly important for the choice of window types when simulating some climates. For example, high-gain windows in moderate climates with a southern exposure, or even adding cellar insulation to walls, typically increase the cooling loads. Thus, the energy consumption results from EnergyPlus as interpreted within BEopt will seek to balance various building elements to address heating, cooling and appliance uses to best reduce energy costs for the cost-optimal selection.

A cooling system may be avoided altogether in temperate climates. The analysis method tends to encourage efficiency options such as shading, insulation and surface solar absorptance that can significantly reduce cooling needs.

3 Results

3.1 Selected energy efficiency measures in Milan (Italy)

The baseline new two-story building is estimated to use 3901 kWh of electricity per year and 54.3 GJ of natural gas for space and water heating (space heating is approximately 44 GJ) in Milan (Italy). When normalized by building floor area, this amounts to 32.5 kWh/m^2 and 0.45 GJ/m^2. The optimization process is designed to find the most cost-effective set of energy efficiency measures related to envelope, appliances, and systems. Measures are evaluated against the cost of electricity and natural gas, considering the cost of producing solar electricity using roof-top photovoltaics. The baseline building has approximately 72 m2 of South facing roof area.

Table 6 shows how in the analysis conducted in the example of Milan the energy efficient and the renewables integration measures were ordered to reach the final design configuration. Beopt and EnergyPlus ran for a total of 2097 simulations in 43 iterations to get to the final target of 90% or greater source energy savings. As shown in the table, the first selected options were the replacement of some appliances with more efficient ones, followed by insulating walls to R-7.2 (0.14 W/m^{2}K), changing windows and other interventions on energy systems. The other measures selected were: improving ceiling insulation to R-10.6 (0.09 W/m^{2}K), insulating the cellar walls on the interior (0.29 W/m^{2}K), reducing building air leakage to 0.6 ACH at a 50 Pa blower door pressure (Passivhaus standard), a 98% efficiency fully condensing gas boiler with improved pipe insulation, 100% efficient lighting and a complete selection of A++ appliances (refrigerator, dishwasher, clothes washer, dryer). An electric feedback system with an automated system to shed plug loads is also selected. During the optimization process, a 4.0 kWp grid-connected PV system is added. It produces all the electricity needed at the site.

This example shows that it is possible to achieve more than 95% primary energy savings (from 103.4 to 4.9 GJ) for a standard new building in Milan with cost-effective measures. This results in lower annualized costs for combined energy and investment expenses even when paying for the upgrades. Table 6 also shows the changes in primary energy consumption, site (final) electricity and natural gas use, incremental and cumulative costs as compared to the baseline building. This type of analysis, illustrated for Milan, was run for all of the evaluated locations.

Table 6. Selected order of energy efficiency measures in Milan (Italy).

Category	**Measure**	**Total (GJ)**	**Electric (kWh)**	**Gas (GJ)**	**Incremental costs (€)**	**Cumulative costs (€)**
Base Case	None	103.4	3901	54.3	0	0
Appliance	A++Air Dryer	99.4	3365	56.1	250	250
Appliance	Efficient lighting	97.1	3115	56.7	320	570
Appliance	A++Refrigerator	95.8	2963	57.0	160	730
Appliance	A++Clothes Washer	93.2	2808	58.3	150	880
Wall insulation	Walls +R.3.3 (RSI 3.3 walls: U: 0.303), ACH 50 (Air changes at 50 Pascal tested building pressure)	73.0	2685	39.0	1177	2057
Windows	40% glazing to South	72.4	2655	38.8	75	2132
Distribution	Hydronic piping to R-2 (RSI 2; U:0.5)	72.0	2647	38.5	39	2171

Category	Measure	Total (GJ)	Electric (kWh)	Gas (GJ)	Incremental costs (€)	Cumulative costs (€)
Air tightness	2 ACH50	70.5	2647	37.1	107	2278
Air tightness	1 ACH50 + High efficiency Mini-split	66.8	2582	34.3	325	2603
Mechanical Ventilation	90%+ ERV (enthalpy recovery ventilator)	64.9	2550	32.9	349	2952
Heating	98% efficient fully condensing boiler	61.5	2550	29.9	392	3344
Air tightness	0.6 ACH	61.1	2553	29.4	134	3478
Roof finish	Dark Tile	61.0	2562	29.2	0	3478
Ceiling Ins	Insulation to R6.7 (U=0.15)	60.5	2559	28.8	202	3680
Appliance	A++ Dishwater	59.8	2515	28.7	160	3840
Windows	Double glass, low-e film with hi-gain G factor, air fill	59.3	2518	28.2	148	3988
Solar PV	4.0 kW PV system	19.2	-1014	28.2	14484	18472
Windows	Double glass, low-e film with hi-gain G factor, air fill, Insulated frame	17.8	-1005	26.8	546	19018
Water Heat	Fully Condensing Gas Water heater	16.6	-1005	25.6	429	19447
Cellar Walls	Cellar Wall: +R1.8 (RSI 1.8: U= 0.56)	15.8	-994	24.9	447	19894
Ceiling Ins	Ceiling to R8.6	15.8	-996	24.6	286	20180
Wall Ins	Wall to R6.3 (U=0.19)	12.8	-1017	22.3	2246	22426
Wall Ins	Wall to R7.2 (U=0.14)	12.0	-1020	21.6	782	23208
Appliance	Feedback & home EMS (energy management system)	9.7	-1275	22.2	620	23828
Cellar Walls	Cellar W to R1.8 (U=0.56)	9.3	-1269	21.7	1732	25560
Windows	Double glass, low-e film with hi-gain G factor; argon fill	9.1	-1272	21.5	-986	24574
Windows	Double glass, low-e film with hi-gain G factor, argon fill, Insulated frame	8.2	-1266	20.8	751	25325
Cellar Walls	Walls to R3.5	7.9	-1260	20.5	456	25781

Category	Measure	Total (GJ)	Electric (kWh)	Gas (GJ)	Incremental costs (€)	Cumulative costs (€)
	(U=0.29)					
Solar Hot Water	Solar water heater $6m^2$	4.9	-1108	16.0	4800	30581

Source: JRC, 2023.

3.2 Sensitivity analysis

The cost of improving the heating system boiler and high efficiency cooling system changes over the course of the BEopt analysis as the necessary size for both systems get smaller and less expensive. The cost of the fully-condensing boiler is that before sizing advantages are incorporated. The incremental costs of more efficient refrigerators and other appliances have been obtained by comparing standard versus A++ products costs for a single manufacturer. However, incremental costs may be higher when comparing across manufacturers.

A sensitivity analysis has been performed on the economic parameters for the Milan case (discount rate, cost of natural gas and electricity and their future price escalation rates). This evaluation showed that, although the order of the measures selected in the optimization and the final NPV are changed, altered rates do not typically alter the final selection of measures within the optimization for the achieved energy savings reduction. Lower energy cost and inflation rates actually result in a lower annualized cost of energy and financing costs. The final point on the curve goes from 2,470 € to 2,363 €.

3.3 Analysis of the results

Within the optimization, the first group of selected measures, as seen in Table 6, are dominated by low or no-cost options (such as roof finish solar absorptance), by the choice of A++ appliances and efficient lighting devices. These measures are highly cost effective and associated with a very steep drop in the annualized costs.

Moreover, the building begins with equally distributed glazing, but the simulation later determines that moving the glazing area to the South face of a building — a no cost option for a new construction — is highly desirable. Architectural features, such as overhangs or awnings, are shown as useful to reduce overheating potential.

Additional wall insulation shows very large energy reductions within the optimization. The optimization process spends much time parametrically analyzing more than a dozen window options with varying glass coatings, solar transmittance or G-factors, fill and framing types. The selection changes over the optimization when heating and cooling system sizes and efficiencies are altered. It is interesting to note, however, that as the building improved thermally, the incremental cost of more efficient heating and cooling systems become negligible as the required size is reduced.

The final selected package of measures has a total incremental cost of 30,581 €. About half of this amount are for a 4.0-kWp PV system and 4,800 € are for a pumped solar water heating system that augmented a 98% efficient fully condensing gas boiler. As seen in Table 6, the efficiency measures dominate the potential cost-effective savings. Thermal building improvements greatly reduce gas consumption while appliance and lighting efficiency improvements are key factors to cut electrical energy use.

The efficiency improvements reduce household natural gas use by 71% (55 to 16 GJ annually) and electricity consumption by 38% (3901 to 2424 kWh/y). After efficiency improvements, a 4.0 kW PV system is able to produce an amount of electricity (3532 kWh/y) that is 1,108 kWh more than the improved building annually requires. The combined total annual source energy needed, considering both efficiency improvements and renewable power generation, is cut by 97% with a similar corresponding reduction in annual CO2 emissions from the household from 6.0 to 0.2 tons.

There are also financial advantages in having a thermally efficient building with solar electric power production. The homeowner annually saves approximately 2,243 € the first year in utility costs (bringing the annual utility cost to less than zero) and, even after accounting for interest expenses, the owner has a positive cash flow.

3.4 Simulations at different EU locations

A comparison between the baseline and the optimized building related to modelled consumptions for electricity and natural gas is summarized in Table 6. This table also shows the changes to electricity and natural gas use, primary source energy consumption, incremental and cumulative cost when compared to the baseline. Costs for appliances are based on data on actual models within an average manufacturer and there may be variations across manufacturers. Solar PV production, annual net electricity consumption, and savings are also reported for the simulated NZEBs in all locations. Source energy savings percentage is computed for both electricity and natural gas consumption. Normalized site energy use can be computed by dividing the annual amounts by 120 m^2.

Table 7. Simulated initial electricity, natural gas and PV electric output for the baseline and optimized NZEB.

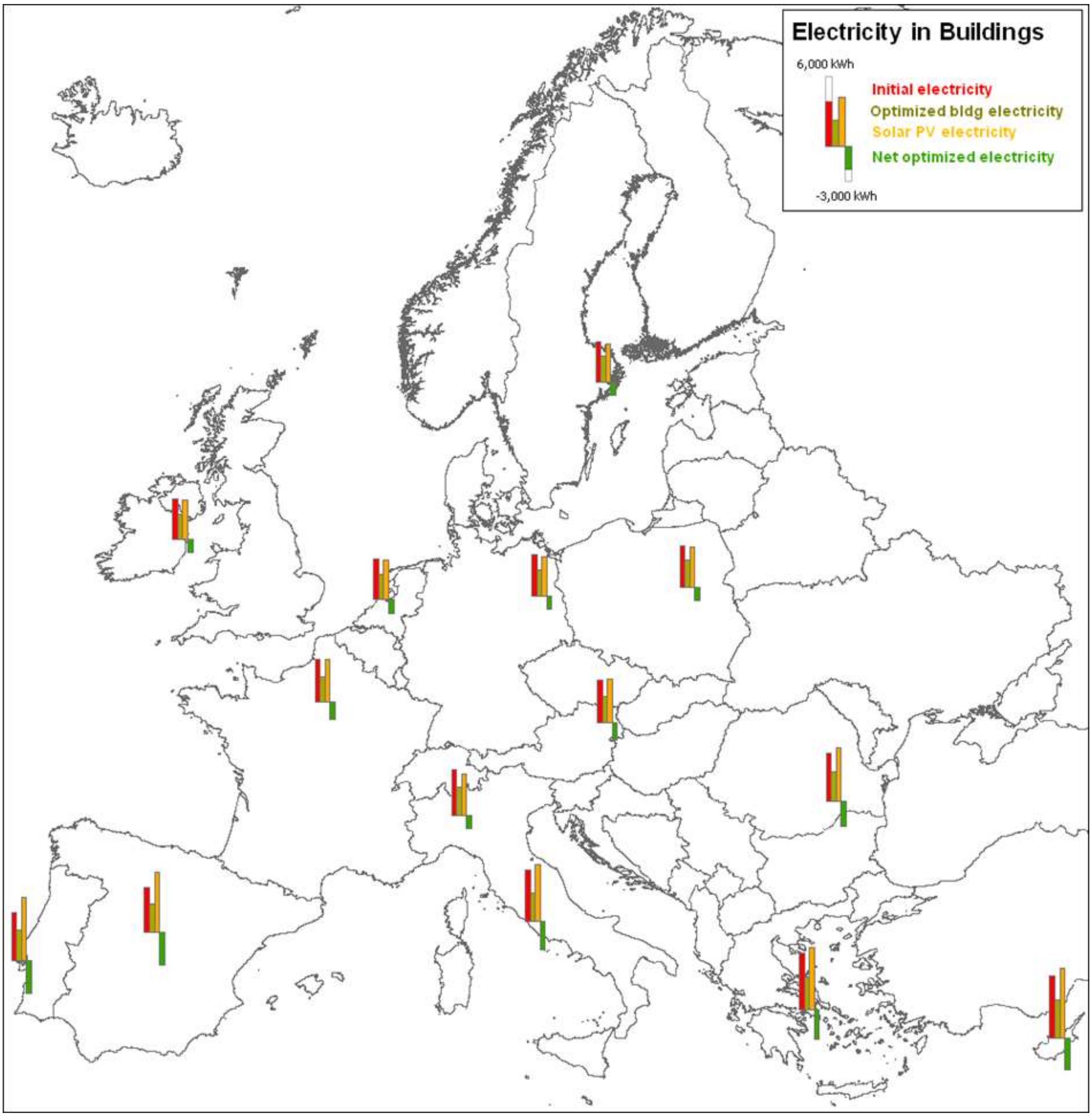
Location	Base Building		Nearly Zero Energy Building			
	Annual Electricity (kWh)	Annual Natural Gas (GJ)	Solar PVH (KWh)	Annual Net (kWh)	Natural Gas (GJ)	Source Savings (%)
Amsterdam	3482	60.2	3437	-1210	15.2	97%
Athens	4938	18.4	5358	-2521	12.5	120%
Berlin	3537	65.1	3371	-1152	18.6	93%
Bucharest	4112	56.9	4660	-2090	21.7	100%
Dublin	3441	59.0	3309	-1143	14.6	97%
Larnaca	5334	11.1	5985	-2708	12.7	123%
Lisbon	4103	16.7	5413	-2831	13.0	128%
Madrid	3889	33.9	5200	-2732	18.1	114%
Milan	3901	54.3	3532	-1108	16.0	95%
Paris	3590	52.6	3605	-1471	18.3	97%
Rome	4373	24.2	4862	-2468	12.5	119%
Stockholm	3508	85.6	3326	-1090	18.9	94%
Vienna	3687	63.5	3801	-1518	17.6	98%
Warsaw	3567	74.6	3447	-1146	21.4	92%

Source: JRC, 2023.

Figure 3 graphically illustrates initial and optimized building electricity consumption together with net annual optimized electricity and solar PV output in each location.

From the data in Table 7, natural gas use varies with heating severity by 6:1 from the lowest consumption location to the highest. Electricity consumption varies less (1.6 to 1.0), being elevated in the warmest locations. Photovoltaic output from the rooftop PV system varies approximately 2:1 from the sunniest location, to the cloudiest. The figure graphically illustrates how initial, optimized building and net annual electricity compares to the solar PV output for each location.

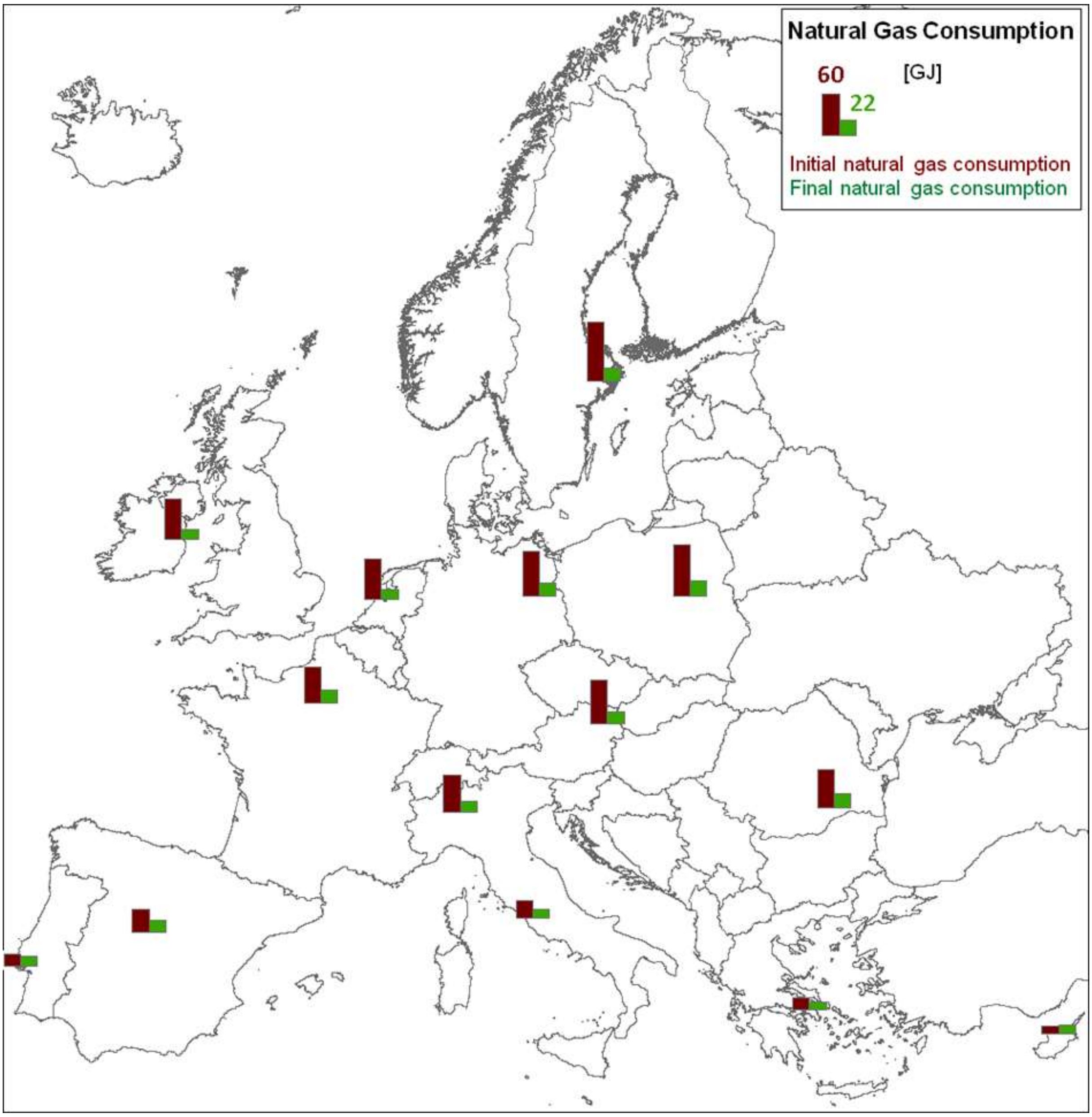
Figure 3. Base building electricity (red) vs optimized building (olive), annual PV power production (orange) and net electricity (green).



Source: JRC, 2023.

Figure 4 reports on map the initial and final gas consumption in all locations.

Figure 4. Simulated natural gas consumption in the base building (red) vs the optimized building (green) before and after the optimization.



Source: JRC, 2023.

After optimization, the building natural gas consumption is much lower than in the initial state except for the sunniest locations.

The optimization results and the selected options reflect climatic conditions. Much greater insulation levels and air tightness are selected in colder and cloudier locations. After the optimization, building natural gas consumption is cut to a low level, particularly for sites in colder climates with elevated heating consumption in the baseline building. It should be noted that including a PV system in the analysis will exclude efficiency measures that are less cost effective than obtaining the same savings from solar systems. If a kWh is produced by this system at a lower cost, the optimization will choose the reduction produced by the PV system rather than by saving that same kWh with an efficiency measure. Low gain windows, light colored tiles, efficient cooling and appliances are important to achieve a positive energy building at low incremental costs. Evaluation for colder locations show similar results with very tight construction indicated with very high insulation levels and triple glazed windows.

4 Conclusions

The EPBD recast requires Member States that all new buildings have to be NZEBs by the end of 2020. NZEBs have to combine efficiency measures and renewables production considering cost-optimal levels of minimum energy performance requirements. The combination between the implementation of NZEBs and the assessment of cost-optimality represents one of the major challenges that Europe is facing.

This report describes the development of an energy simulation and cost optimization model to identify the NZEB cost-optimal design of a new residential building prototype. This building has been located in European cities having different climatic conditions. The model has been run in different European locations. Results have been analysed in detail for the case of Milan (Italy) and for all locations in terms of primary energy sources.

Results show the feasibility of EU requirements for new NZEBs constructions located in different European cities. They show that it is possible to reach a very low energy design in new buildings with source energy savings beyond 90% compared to the baseline case. The way in which this achievement is accomplished at the lowest cost differs by location. However, results point out in all locations the importance of both renewables and energy efficiency measures to reach cost-effective NZEBs. In particular, efficient lighting and appliances strongly impact the results and should be included in the energy performance assessment.

Thermal improvements are strongly dependent on the relative heating load in a given city. The most common approach foresees a combination of good insulation, windows, building tightness as well as Class A++ appliances, lighting, and home energy management systems along with a PV system.

In each location, the optimized building has less than zero net electricity consumption on an annual basis. Natural gas consumption for space heating and water heating is reduced by 70% in most locations. However, electricity neutrality is only achieved if home lighting and appliances are optimized at the same time that the building technical systems are addressed. Efficiency measures are able to cut household appliance electricity by 35% or more in most cases.

Results have shown different optimization results between cold and cloudy locations, such as Brussels, and sunny ones, such as Lisbon. For instance, in warmer locations, interior appliance efficiency measures are selected earlier as heating loads are not as significantly increased. In case of the warmest locations, cooling loads may be reduced. In colder climates, insulation and building tightness appear much more important.

The developed model can be useful to identify the cost-optimal solutions in terms of high energy performance and global costs in different climates. It supports a cost-effective NZEBs design and decision making, facilitating the management of many parameters and the selection of different configuration options in new constructions.

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