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Comprehensive Modeling of Optimal Paths to Reach Nearly Zero Energy Buildings (nZEBs) for New Constructions in Europe

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Abstract

As established by the recast of the European Union (EU) Directive on Energy Performance of Buildings (EPBD), all new buildings have to be nearly zero energy buildings (nZEBs) by the end of 2020. However, reaching this result considering cost-optimality is still an open challenge. Balancing renewable power generation with energy efficiency to reach the nZEB target is a key goal of all EU Member States.

We describe results obtained from the modeling of nZEBs for new constructions in Europe using the energy performance software *EnergyPlus*. The model performs hourly sequential simulations showing how to best achieve nearly zero energy home design at the lowest possible cost in 36 representative locations across Europe. We adapted the model to run in a new residential building prototype using local hourly climatic data, relevant construction methods, cost data and unit energy consumption. A novel aspect is the inclusion of future climate change relative to estimated cooling loads. We also performed a sensitivity analysis both on energy and economic parameters as well as PV costs, accounting for the need of short term electrical storage.

A key finding of the research is that energy reductions of 80% and beyond are economically feasible for new constructions, although the mix of selected measures varies strongly with climate. Results show how a broad approach to efficiency mixed with renewables is feasible in each location at different costs. In particular, we illustrate how exclusion of lighting and appliances results in sub-optimal solutions, especially for electricity use which has a huge impact on greenhouse gas emissions.

1. Introduction

Residential and commercial buildings are globally estimated to consume approximately 40% of primary energy and to be responsible for 24% of greenhouse emissions [1]. Nearly, net or positive energy buildings have been demonstrated in many monitored projects in Europe. In particular, very low energy homes have proven the Passivhaus approach, although the trade-off of incremental measures against high performing appliances and renewable energy generation has not been completely addressed.

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 Europe's building stock [2][3][4][5].

A nZEB is 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 of the EPBD recast states that Member States (MS) shall ensure that new buildings occupied by public authorities and properties are Nearly Zero Energy Buildings (nZEBs) by December 31, 2018 and that 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 importance of integrating the nZEBs concept into National Building Codes and International Standards is widely recognized [6].

It is up to MS to define what “a very high energy performance” and “to a very significant extent by energy from renewable sources” exactly constitute for them. Other open issues concern how to combine nZEBs with the requirement to optimize the investments involved and the associated reduction in energy costs; and how to carry out performance level calculations in each country [7].

In order to address this need, we identify an approach to harmonize efficiency and the use of renewable energy sources in specific locations.

2. Research Objectives

Nearly zero energy buildings (nZEBs) have to combine efficiency, thermal improvement measures and renewable energy sources (RES) production. The authors attempt to address this issue through the use of a comprehensive building energy simulation tool which considers European weather data linked to a cost database followed by an exhaustive optimization approach. nZEBs, for the purposes of our study, are defined as buildings saving 90% of source energy for all end uses in reference to a baseline case. The main key points of this approach are:

- The methodology is aimed at identifying the lowest cost path to reach the nZEB target;
- Hourly weather data is used for selected European locations;
- A detailed thermal analysis model is performed to derive space heating, space cooling and water heating consumption;
- Both building thermal performance and appliance efficiencies are taken into account in the analysis;
- Renewable energy electricity production is directly compared to the cost of energy savings obtained by efficiency technologies;
- Costs of competing components along with their life expectancy, replacement costs, salvage value etc. are evaluated in a detailed way;
- Results are compared to varying construction techniques, materials, equipment, energy costs, and other performance parameters variations for sensitivity analysis;
- Location results allow the identification of the most suitable cost-effective methods to reach nZEBs in European Member States (MS).

We used the BEopt & EnergyPlus simulation programs to identify how to reach Nearly Zero Energy Buildings (nZEBs) at the lowest possible cost. BEopt uses the Energy Plus and TRNSYS simulation programs for its calculations of the savings of specific options in the optimization process.

2.1 Building Energy Simulation

BEopt is an Energy simulation tool, 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 [8].

This model estimates hourly household heating, cooling, water heating and appliance loads within EnergyPlus. Fundamental building thermodynamics are estimated via finite difference conduction functions using a multi-zone representation that allows a robust evaluation of transient thermal phenomena. A variety of energy carriers can be simulated. The simulation has been compared to real buildings to verify its potential to replicate measured energy use in cold versus hot climates [9].

The simulation model has been adapted to run in European climates by adding hourly International Weather for Energy Calculations (IWEC) weather data files, converting to metric inputs and adapting cost data to the European format. Using similar inputs, favorable comparisons have also been produced against the Passivhaus Planning Package (PHPP) software [10]. Solar thermal and solar photovoltaic (PV) system output is evaluated using the state-of-the-art TRNSYS simulation [11].The economic optimization method is consistent with established procedures for nZEBs cost-optimality in the EU. BEopt contains a library of approximately 150 energy efficiency options. The software’s 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.

To enable the optimization, a library of measures is defined with their characteristics as well as their specific costs, life expectancy, operation, maintenance, and replacement costs. Renewable energy production is evaluated using a photovoltaic (PV) simulation (Transient Simulation Program: TRNSYS) as well as prediction of solar water heating performance. For a given location, this allows the cost effectiveness of energy efficiency measures to compete directly with the cost of renewable energy production to determine the most convenient path to near zero energy. Even in cold climates, this method offers some advantages against the standard *Passivhaus* approach as it is possible to reach zero energy performance at a lower cost [12].

The optimization model evaluates the entire suite of options and selects the option with the highest present value savings. It incorporates this option, and re-simulates all available options. The process continues in this manner until a favourable cost ratio of lifecycle savings is reached or until zero energy is achieved using RES. The sequential search technique has a number of advantages. Not only does it attempt to reach the established target, but it does attempt to locate 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. Another advantage is that discrete building options are evaluated, reflecting realistic construction options. This means that specific materials, equipment and appliances are evaluated given realistic features of available products. Finally, near-optimal alternative designs are also identified within the optimization process.

2.2 Economic Parameters

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

Cost effectiveness calculations are based on the present value of life-cycle costs and last over an analysis period of 30 years. The procedure for estimating life-cycle cost calculations are well documented [13]. The assumed economic parameters are shown in Table 1 for Milan.

Table 1. Economic Parameters for 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%
Current Electricity Price	€0.25/kWh
Current Natural Gas Price	€16.10/ GJ or €0.058 kWh $_{gas}$

They are based on recommended guidelines supplementing Directive 2010/31/EU [14]. The assumed costs, service lives, and maintenance fractions for each of the hundreds of efficiency measures considered are given in an Excel 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€/tCO$_2$ in 2020 to 39€/tCO$_2$ in 2020. Although the selected rates are based on the EC guidance, we performed sensitivity analysis for the Milan optimization case, given current prevailing conditions in spring 2015, which suggest lower inflation and financing rates. The new parameters for sensitivity 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% [15].

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. 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 leverage 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 our analysis, the PV system has often been installed midway through the optimization process with further efficiency measures still needed at the end to achieve the nZEB target.

2.3 Analytical Approach to Climatic Variation

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. However, also of importance is the relative need for heating and cooling in that location in function of its climate.

For the analysis we selected locations across Europe in order to have at least one representative city of each MS. Other cities were added in order to have a good geographic coverage of possible climates. Given the very large degree of climatic variation, we simulated 36 locations spread across the various countries. These data came from the IWEC hourly weather data that are then used by EnergyPlus simulation to predict heating and cooling, and by TRNSYS to predict how solar power production varies over time. The simulated locations are listed in Table 2.

Table 2: Simulated locations

Location name	Country
Amsterdam	Netherlands (NL)
Athens	Greece (EL)
Berlin	Germany (DE)
Bordeaux	France (FR)
Bratislava	Slovakia (SK)
Brussels	Belgium (BE)
Bucharest	Romania(RO)
Copenhagen	Denmark (DK)
Debrecen	Hungary (HU)
Dublin	Ireland (IE)
Geneva	Switzerland (CH)
Kaunas	Lithuania (LT)
Kiev	Ukraine (UA)
Koln	Germany (DE)
Larnaca	Cyprus (CY)
Lisbon	Portugal (PT)
Ljubljana	Slovenia (SI)
London	Great Britain (UK)
Madrid	Spain (ES)
Marseille	France (FR)
Milan	Italy (IT)
Moscow	Russia (RU)
Munich	Germany (DE)
Oslo	Norway (NO)
Paris	France (FR)
Palermo	Italy (IT)
Prague	Czech Republic (CZ)
Rome	Italy (IT)
Salzburg	Austria (AT)
Seville	Spain (ES)
Sofia	Bulgaria (BG)
Stockholm	Sweden (SE)
Stuttgart	Germany (DE)
Tampere	Finland (FI)
Vienna	Austria (AT)
Warsaw	Poland (PL)

3. Prototype New Residential Building Characteristics

The methodology is now illustrated for Milan (Italy). A standard new house of 120 m^2 above grade with a full cellar has been considered. This building is derived from a prototype described in a recent study by Ecofys GmbH and the Danish Building Research Institute [16]. Its main characteristics are summarized in Table 3. The same table reports system properties, insulation levels, airtight equipment efficiencies and appliances. This building is fixed to a standard energy performing starting point for the optimization process of this research. We chose a baseline of 80% incandescent even though lighting is currently in a state of rapid change in the EU. It must be noted, however, that the lighting segment is so cost effective that even assuming a 30% saturation of incandescent, that change to CFL/LED would still be among the first measures chosen within the optimization.

Table 3. 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	20^{o}C for heating, cooling 23^{o}C	
Hot Water	155 l insulated boiler in cellar providing 120 l per day at 55^{o}C	
Mechanical Ventilation	20.3 1/s continuous with 72% efficient ERV	
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	6m^2 closed-loop system

We used a water heating load of 120 l/day. The size of the potential PV system (4.0 kWp) has been chosen based on available south facing roof area, selecting efficient modules and allowing the possibility for installing a 6m^2 solar water heating system. According to [17], temperature in Europe is likely to increase in the near future. Considering that the simulated new buildings would be used for decades, we consider adjustments to simulation assumptions to account for this change. Typically, for evaluating cooling loads in residential buildings, a thermostat cooling set-point of approximately 25 °C is assumed. To compensate higher cooling loads in future, we adopted a set-point of 23 °C. This change is in line with recent climate predictions [18], 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.

Also, we include a mini-split cooling system 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.

4. Simulation Results

When simulated for Milan (Italy) the baseline new building is estimated to use 3901 kWh per year and 54.3 GJ of natural gas for space and water heating (space heating is approximately 44 GJ). 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.

Table 4 shows the selected measures from the analysis conducted in the Milan example to reach the final design configuration. Beopt and EnergyPlus ran a total of 2097 simulations in 43 iterations to get to the final target of 90% and beyond source energy savings. As shown in the table, selected options comprise insulating walls to R-7.2 (0.14 W/m^{2}K), 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 50Pa 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.

Our example analysis shows the capability to achieve more than 95% source energy savings in Milan with cost effective measures. This results in lower annualized costs for combined energy and investment costs when paying for the upgrades. Table 5 also shows the changes to electricity and natural gas use, source energy consumption, and incremental and cumulative costs compared to the baseline.

Table 4. Selected Order of Energy Effciency Measures for the Optimization in Milan (Italy).

Case	Category	Measure	Total GJ	Electric (kWh)	Gas (GJ)	Increm. (€)	Cum. Total (€)
1	Base Case	None	103.4	3901	54.3	0	0
2	Appliance+	A++Dryer + Win:Dbl_LE_LowG	99.4	3365	56.1	250	250
3	Appliance+	Eff. Lighting+ Lt. tile	97.1	3115	56.7	320	570
4	Appliance+	A++Refrig	95.8	2963	57.0	160	730
5	Appliance+	A++Clothes Washer	93.2	2808	58.3	150	880
6	Wall Ins.+	Walls: +R3.3, 3 ACH50	73.0	2685	39.0	1177	2057
7	Windows+	40% Glz to south, Induction rnge	72.4	2655	38.8	75	2132
8	Distribution	Hydronic piping to R-2	72.0	2647	38.5	39	2171
9	Air Tightness	2 ACH50	70.5	2647	37.1	107	2278
10	Air Tightness	1 ACH50 + Hi Eff Mini-split	66.8	2582	34.3	325	2603
11	Mech. Ventilation	90%+ ERV	64.9	2550	32.9	349	2952
12	Heating Sys.	98% eff. fully condensing boiler	61.5	2550	29.9	392	3344
15	Air Tightness+	0.6 ACH	61.1	2553	29.4	134	3478
16	Roof Finish	Dark Tile	61.0	2562	29.2	0	3478
17	Ceiling Ins	Insul to R 6.7	60.5	2559	28.8	202	3680
18	Appliance	A++ Dishwasher	59.8	2515	28.7	160	3840
19	Windows	Dbl_LE_HiGain_Ar Fill	59.3	2518	28.2	148	3988
20	Solar PV	4.0 kW PV system	19.2	-1014	28.2	14484	18472
21	Windows	Dbl_LE_Hi gain_Air Fill_Ins frame	17.8	-1005	26.8	546	19018
22	Water Heat	Fully Condensing Gas WH	16.6	-1005	25.6	429	19447
23	Cellar Walls	Cellar Wall : +R1.8	15.8	-994	24.9	447	19894
24	Ceiling Ins	Ceiling to R8.6	15.8	-996	24.6	286	20180
25	Wall Ins	Wall to R 6.3	12.8	-1017	22.3	2246	22426
26	Wall Ins	Wall to R 7.2	12.0	-1020	21.6	782	23208
27	Appliance	Feedback & home EMS	9.7	-1275	22.2	620	23828
28	Cellar Walls	Cellar W to R 1.6	9.3	-1269	21.7	1732	25560
29	Ceiling Ins	Dbl_LE_HiGain_Ar Fill	9.1	-1272	21.5	-986	24574
30	Windows	Dbl,_LE,_HiG_Ins_frame_ArFill	8.2	-1266	20.8	751	25325
31	Cellar Walls	Walls to R 3.5	7.9	-1260	20.5	456	25781
32	Solar Hot Water	Solar water heater ($6m^2$)	4.9	-1108	16.0	4800	30581

*The cost of improving the heating system boiler and hi-efficiency cooling system changes over the course of the BEopt analysis. The cost of the fully-condensing boiler is that before sizing advantages are incorporated.

** The incremental costs of more efficient refrigerators and other appliances were obtained by comparing standard versus A++ product costs within a single manufacturer. Note that incremental costs may be higher when comparing across manufacturers.

The sensitivity analysis performed on the economic parameters for the Milan case show that, although the order of the measures selected in the optimization and the final NPV are changed, the lower rates do not change the final selection within the optimization for the achieved energy savings reduction. The lower inflation rates actually result in a lower annualized cost of energy and financing costs (final point on the curve goes from 2470 € to 2363 €).

Within the optimization, the first group of selected measures are dominated by low or no-cost options (such as roof finish solar absorptance), by choice of A++ appliances and efficient light. 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.

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 30581 €. 14484 € of this amount are for a 4.0-kWp PV system and 4800 € are for a pumped solar water heating system that augmented a 98% efficient fully condensing gas boiler. As seen in Table 4, 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/yr). After efficiency improvements, a 4.0 kW PV system is able to produce an amount of electricity (3532 kWh/yr) that is 1108 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 CO_2 emissions from the household from 6.0 to 0.2 tonnes.

There are also large financial advantages in having a thermally efficient building with solar electric power production. The homeowner annually saves approximately 2243 € 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. A comparison between the baseline and the optimized building related to simulated initial annual consumptions for electricity and natural gas is summarized in Table 5. Table 5 also shows the changes to electricity and natural gas use, source energy consumption, incremental and cumulative cost when compared to the baseline. It may be noted that these costs for appliances were based on data on actual models within an average manufacturer and there may be variantions across manufacturers. Solar PV production from the PV system, annual net electricity consumption, and savings are also reported for the simulated nZEBs in the 36 locations.

Table 5: Simulated Initial Electricity, Natural Gas and PV electric output for the Baseline and Optimized Nearly Zero Energy Buildings in the 36 Locations

IWEC Location	---- Base Building ----		---- Optimized 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%
Bordeaux	3574	36.2	4270	-1832	16.2	104%
Bratislava	3798	59.3	4051	-1838	21.0	102%
Brussels	3532	59.9	3115	-841	16.4	92%
Bucharest	4112	56.9	4660	-2090	21.7	100%
Copenhagen	3491	73.7	3476	-1257	20.6	93%
Debrecen	3860	60.6	4191	-1955	21.8	99%
Dublin	3441	59.0	3309	-1143	14.6	97%
Geneva	3731	54.4	3963	-1785	19.9	99%
Kaunas	3579	84.7	3418	-1155	18.7	95%
Kiev	3669	74.5	4138	-1829	21.2	98%
Köln	3523	60.7	3288	-1005	16.9	93%
Lamaca	5334	11.1	5985	-2708	12.7	123%
Lisbon	4103	16.7	5413	-2831	13.0	128%
Ljubjana	3719	64.8	3572	-1254	18.8	94%
London	3470	55.0	3487	-1263	13.9	99%
Madrid	3889	33.9	5200	-2732	18.1	114%
Marseille	4174	31.0	5209	-2630	14.0	118%
Milan	3901	54.3	3532	-1108	16.0	95%
Moscow	3640	92.1	3412	-1111	21.5	92%
Munich	3546	73.0	3831	-1545	20.2	96%
Oslo	3508	83.9	3142	-894	19.5	92%
Paris	3590	52.6	3605	-1471	18.3	97%
Palermo	5015	11.4	5457	-2397	11.6	121%
Prague	3523	76.5	3239	-1023	15.9	95%
Rome	4373	24.2	4862	-2468	12.5	119%
Salzburg	3590	64.1	3593	-1348	17.5	97%
Seville	5035	12.9	5730	-2855	10.2	130%
Sofia	3757	59.3	3614	-1272	16.8	96%
Stockholm	3508	85.6	3326	-1090	18.9	94%
Stuttgart	3558	65.4	3743	-1445	17.7	97%
Tampere	3526	101.7	3361	-1087	23.4	91%
Vienna	3687	63.5	3801	-1518	17.6	98%
Warsaw	3567	74.6	3447	-1146	21.4	92%

From data in Table 5, we see that natural gas use varies with heating by a factor of 6 from the lowest consumption location (Palermo) to the highest (Tampere). Electricity consumption varies less (1.6 to 1.0), being elevated in warmer locations. Photovoltaic output from the rooftop PV system varies approximately by a factor of 2 from the sunniest location (Seville), to the cloudiest (Brussels). Figure 1 graphically illustrates initial and optimized building electricity consumption together with net annual optimized electricity and solar PV output in each location.

From the tabular data above, we see that natural gas use varies with heating severity by 6:1 from the lowest consumption location (Palermo) to the highest (Tampere, Finland). 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 (Seville, Spain), to the cloudiest (Brussels, Belgium). Figure 2 graphically illustrates how initial, optimized building and net annual electricity compares to the solar PV output for each location.

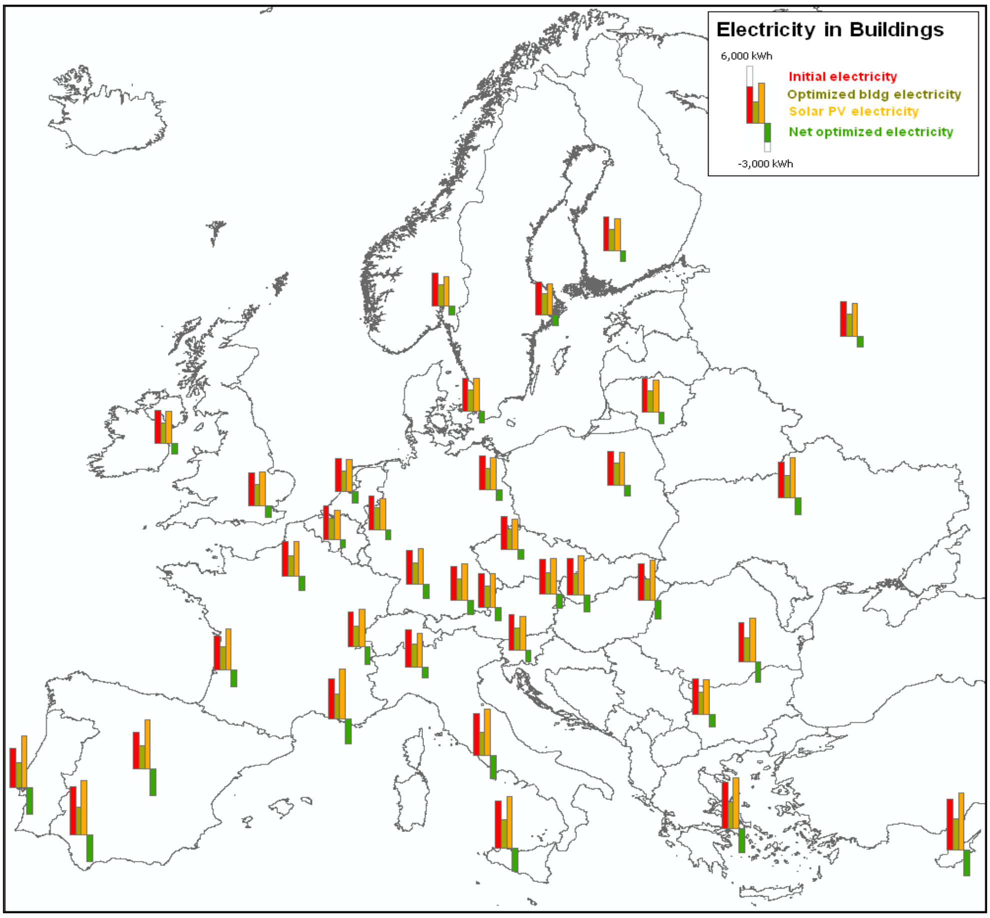

Figure 1: Base building electricity (red) v. optimized building (olive), annual PV power production (orange) and net electricity (green)

The optimization results and option selections reflect climatic realities with much greater insulation levels and air tightness being selected in the colder and cloudier locations. After optimization, the building natural gas consumption is much lower than it begins except for the sunniest locations (Figure 2).

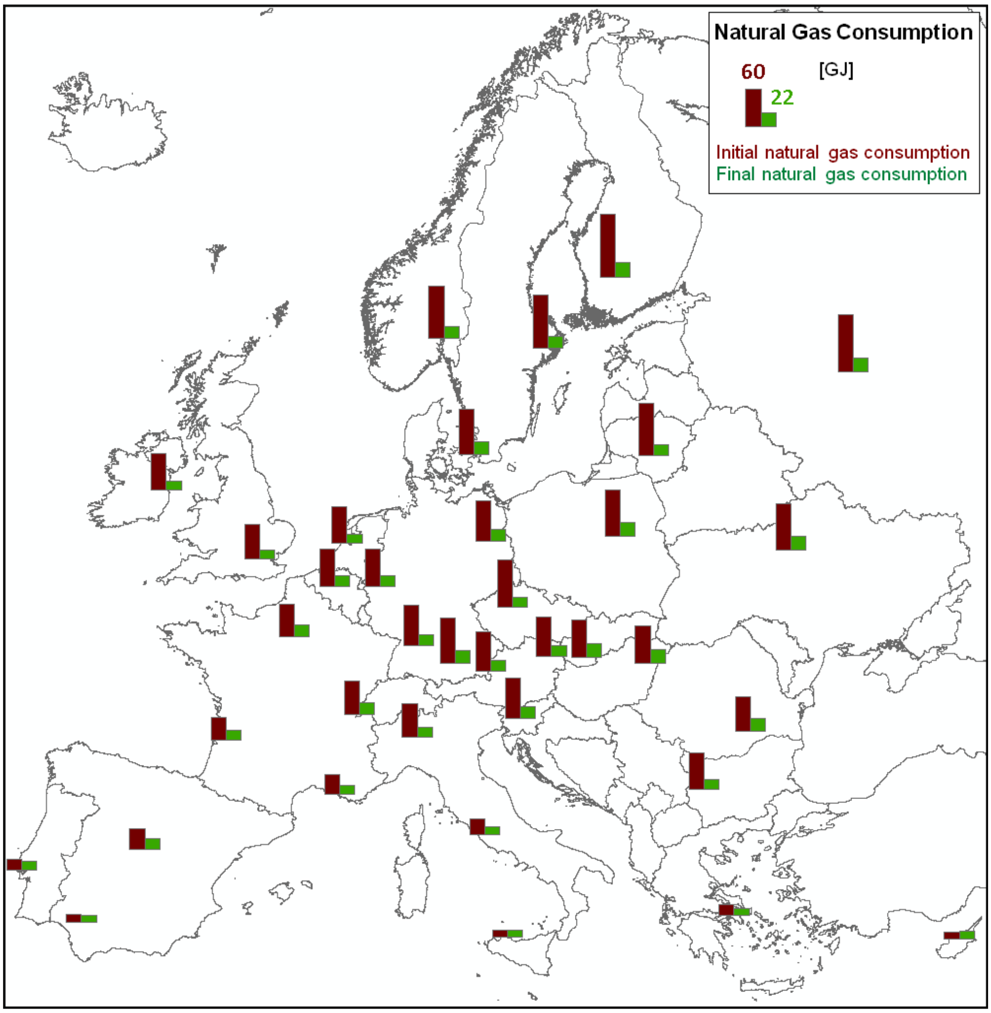

Figure 2: Simulated natural gas consumption before and after the house optimization

The optimization results and the selected options reflect climatic conditions. Much greater insulation levels and air tightness are selected in colder and cloudier locations. It can be seen in Table 4 that after 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 achieving a positive energy building at low incremental costs. Evaluation for colder locations such as Oslo, Moscow, Tampere and Stockholm showed similar results with very tight construction indicated with very high insulation levels and Passive House type windows.

4.1 Importance of Considering the Need for Electrical Storage for Solar PV Power

A point can be made that efficiency may be more valuable than renewable energy production. This is due to the fact that efficiency reduction occurs at precisely the time it is needed whereas production of renewable energy may not be coincident with energy needs. However, 5- 10 kW battery storage systems are rapidly becoming available to help with short term electrical storage for renewable power. Still, such systems increase the cost of such hybrid grid tied storage systems.

For instance, although PV output may match well to cooling demand and appliance energy use, it is very much out of phase, both daily and seasonally, with space heating demand. Although today all grid-connected PV energy can be effectively absorbed by the larger utility grid, this may not be true in the long run when PV saturation grows exponentially with dropping costs of solar components and installation. However, for the long term, Feist (2014) with the Passivhaus Institute has recommended a "Primary Energy Renewable (PER)" factor to adjust for the fact that PV does not match well, in particular, with heating demand, and that novel solutions will be required to provide long term storage. Schneiders and Feist (2012) estimated that realistic values of PER vary from 1.8 – 2.1 through the use of heat pumps, although this may be lower in cooling-dominated locations [19]. For the sake of simplicity, we assumed a PER of 2.0 for a sensitivity analysis. In a sense, this says that each kWh of PV generation is half as valuable as a kWh of efficiency savings. While this may be overstating the differences, particularly when many buildings are considered with evolving short-term storage, we performed a sensitivity analysis to see how this adjustment might influence results.

To assess the impact, we conservatively estimated that an 8 kW PV array on the prototype building would be needed to provide 4 kW effectively considering losses incurred to achieve long term storage. Thus, even assuming future reductions in PV array costs, we assume that the cost of providing an effective future system with storage would be twice the cost of a grid-tied system today. We then re-simulated our assessment for the three benchmark climates of Milan, Lisbon and Stockholm and evaluated results. Generally, this analysis argued for more insulation, although PV was still selected as the final option to reach nZEB status. This is because, even though insulation and more efficiency equipment can greatly reduce heating and cooling loads due to the doubled cost limit, some appliance and lighting loads are non-compressible beyond currently achievable limits and some renewable generation is necessary to make up for this shortfall. In Milan, the only difference was that R 14.1 insulation was justified rather than R10.6 before the larger and more expensive PV system was added at the end of the optimization. In colder Stockholm, there were no differences at all in the optimization other than the fact that the PV system was the last option selected. However, in the milder climate of Lisbon, there were a number of differences: Passivhaus level of airtightness was selected along with the highest efficiency ERV, a fully condensing 98% efficient gas furnace, R 6.7 ceiling insulation and a more efficient dishwasher and feedback with a home energy management system.

It is noteworthy that even doubling the effective cost of PV and installing other more cost effective efficiency measures up to that point, it was impossible to use efficiency alone to reach a nZEB criteria if an 80% annual source energy reduction was the metric. In Milan, the efficiency measures prior to PV installation yielded at 57% reduction (96% after PV installed). In Lisbon, the installed efficiency measured were only able to drop baseline consumption by 47% before the PV system was added, which then resulted in 142% source energy savings, even devaluing its electricity production by 50%. Whereas, Passivhaus type construction is commonly considered to reach a reduction of 80% in space heating, unless appliances are aggressively improved non-space heat electricity remains high and unaddressed. Table 7 below summarizes these recommendations by climate.

Table 7. Indicated Residential Building Thermal Integrity and Equipment Levels by Location as evaluated in Optimization Process assuming Primary Energy Factor= 2.0

Site	Wall	Ceiling	Window	ACH	Solar Hot	Ext
Location	-----(W/m2-K)-----		Type	@50Pa	Water	Finish
Amsterdam	0.15	0.07	DH_Ins, Ar	0.3	Yes	Dark
Athens	0.25	0.15	DH_Ins	0.6		Med.
Berlin	0.15	0.07	PH_H	0.3	Yes	Dark
Bordeaux	0.15	0.09	DH_Ins, Ar	0.6	Yes	Med.
Bratislava	0.15	0.09	DH_Ins, Ar	0.6	Yes	Dark
Brussels	0.15	0.07	PH_H	0.3	Yes	Dark
Bucharest	0.15	0.09	DH_Ins, Ar	0.6	Yes	Dark
Copenhagen	0.15	0.07	PH_H	0.3	Yes	Dark
Debrechen	0.25	0.15	DH, Ar	0.6		Med.
Dublin	0.15	0.07	DH_Ins, Ar	0.6	Yes	Dark
Geneva	0.15	0.09	DH_Ins, Ar	0.6	Yes	Dark
Kaunas	0.15	0.07	PH_H	0.3	Yes	Dark
Kiev	0.15	0.09	DH_Ins, Ar	0.6	Yes	Dark
Köln	0.15	0.07	PH_H	0.6	Yes	Dark
Larnaca	0.25	0.19	DL	0.6		Light
Lisbon	0.25	0.15	DH, Ar	0.6		Med.
Ljubjana	0.15	0.07	DH_Ins, Ar	0.6	Yes	Dark
London	0.15	0.07	DH_Ins, Ar	0.6	Yes	Dark
Madrid	0.25	0.12	DH_Ins	0.6		Med.
Marseille	0.25	0.12	DH_Ins	0.6		Med.
Milan	0.15	0.07	DH_Ins, Ar	0.6	Yes	Dark
Moscow	0.15	0.07	PH_H	0.3	Yes	Dark
Munich	0.15	0.07	DH_Ins, Ar	0.3	Yes	Dark
Oslo	0.15	0.07	PH_H	0.3	Yes	Dark
Paris	0.15	0.07	DH_Ins, Ar	0.6	Yes	Dark
Palermo	0.25	0.19	DL	0.6		Light
Prague	0.15	0.07	PH_H	0.3	Yes	Dark
Rome	0.25	0.12	DH_Ins	0.6		Med.
Salzburg	0.15	0.07	DH_Ins, Ar	0.6	Yes	Dark
Seville	0.25	0.15	DL	0.6		Light
Sofia	0.15	0.07	DH_Ins, Ar	0.6	Yes	Dark
Stockholm	0.15	0.07	PH_H	0.3	Yes	Dark
Stuttgart	0.15	0.07	DH_Ins, Ar	0.6	Yes	Dark
Tampeve	0.15	0.07	PH_H	0.3	Yes	Dark
Vienna	0.15	0.07	DH_Ins, Ar	0.6	Yes	Dark
Warsaw	0.15	0.07	PH_H	0.3	Yes	Dark

Codes:
Wall/Cellar/Roof/ceiling: insulation levels in W/m2-K
Windows: D= double glazed with low-e coating, H= high solar transmittance (G-factor); L= low-gain, Ins=insulated window frame; Ar= argon fill, PH_H= Passivhaus triple-glazed window with highly insulated frame and Hi gain characteristics (U= 0.74 W/m2-K, G=0.5)
ACH= house air tightness at 50 Pa blower door pressurization
Hot Water Boiler: fully condensing = 98%
Solar Hot Water = with 6 m^2 solar hot water heating system as auxiliary to boiler
Exterior Finish= indicated optimal color (solar absorptance) of roof and wall elements.

Note that although not shown, all energy efficient lighting and appliances (refrigerator, washer, dryer, dishwasher and home energy management system are cost effective in all locations from the optimization and key to satisfactory performance in reaching the nZEB objective. Also cost effective in each location is a high efficiency 98% efficient condensing boiler with 0.5 W/m^{2}K hydronic pipe insulation. We also note from the simulations that good pipe insulation is potentially important to prevent excessive internal heat gains which can drive cooling loads in milder locations.

With the indicated level of air tightness at the locations, a 90%+ HRV mechanical ventilation system was found justified. Solar water heating is indicated in most colder climates for offsetting water heating needs. However, the fact that solar water heating does not appear in locations such as Madrid should not be interpreted as lower effectiveness, but rather less need after a 4 kW PV array is installed to reach the net zero goal in milder climates.

The window selection in the above table is highly dependent on the cost data used for the optimization. Passivhaus type windows– which had approximately a 50% cost premium over advanced double-glazed designs in data provided by *Ecofys (*which have a U-value of ~1.14 W/m2-K*)*, show as cost effective in the colder climates, but not in the milder locations in our analysis.[1] However, as described within the Passivhaus design process, there may be comfort reasons to have very low conductances for windows, beyond the economics alone. However, the window optimization process does yield very useful information showing where low gain versus high gain designs are desirable as well as where highly insulated assemblies are important.

Interestingly, the analysis also shows that tight construction with high efficiency heat recovery is selected in all locations. Indeed, levels even tighter than Passivhaus tightness are desirable in colder regions to reduce heating needs. Although a minor influence, building exterior finish for stucco walls and for roofs shows the expected behaviour: colder locations call for darker surfaces, while hotter locations such as Cyprus indicate light colored roofs and walls and roofs are helpful to control cooling needs at no cost.

Even using a PER factor of 2, solar will still be installed, however, since its power production is still needed to reach nearly zero energy. We conducted a sensitivity analysis assuming the costs of PV generated electricity were twice was what assumed in our base case (€7/Watt). At this cost level much greater levels of insulation and airtightness are called for in colder locations, although impacts in milder Mediterranean locations are modest. It also must be noted that since the study was begun that the cost of installed PV system in Italy and Germany have fallen from €7/Watt to €/4/Watt or less so that much of the above apparent difference has already vanished.

4.2 Importance of Appliances and Lighting to Obtain Lowest Cost nZEBs

Appliances and lighting are not be included in energy performance assessment according to current legislation. However, our results indicate that this exclusion significantly limits achieved energy savings—particularly for electricity—and it would require an increase of PV production to reach similar energy savings. It should be pointed out that the assumptions made for Passivhaus assumed extremely efficient appliances and very low water heating loads [20], although this fact is sometimes overlooked in considering that standard.

To illustrate the importance of efficient lighting and appliances, we have performed the same optimization analysis of Milan and Lisbon with appliances and lighting not available within the optimization. Results show that achieved energy savings are lower in both locations. For the same building prototype, source energy reductions are lowered from 96% to 86% in Milan, and from 129% to 116% in Lisbon. In particular, the exclusion of lighting and appliances leads to compromised household electricity efficiency. In Milan, this results in a loss of 1466 kWh/year savings.

The authors are aware of the fact that some of the lighting and appliances are portable and are difficult to rate and certify with buildings due to installation or changes post occupancy. However, our analysis still points out that achieving these efficiency levels for lighting and appliances remains critical to achieving NZEBs, particularly for reducing electricity consumption. This may require that

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[1] Andreas Hermelink, "Windows costs and condensing boilers," Ecofys, memo to D. Parker, 12 January 2012.

certification sign off be delayed until after appliances and lighting are installed. The impact of this exclusion can be quantified in reduced electricity savings (only 141 kWh per year corresponding to 4%). The expensive output of the PV system is partly wasted to cover inefficient appliances, the net reduction in electricity use from adding the PV is reduced by 38%. If there is a larger roof-space, this could be offset by more PV, but at a higher incremental cost. Results also show that considering appliance and lighting is progressively more important in warmer climates where lower internal heat gains can reduce potential space cooling. Generally, we have found that more efficient appliances and light efficiency are cost effective for new residential buildings across MS and different climates. Appliances exclusion also makes the nZEB target more expensive, particularly in colder locations. The additional costs over baseline standard practice to reach 90% and beyond savings increases from 31847 € to 43302 € in Milan. In Lisbon, the costs are nearly the same, but with wider differences in electricity reductions (a loss in electricity savings of 990 kWh/yr).

Our results clearly indicate that including appliance and lighting in the optimization process is important to achieve nearly zero energy buildings at the lowest cost. Moreover, the inclusion of lighting and appliances in the nZEB evaluation will become progressively more important in the near future as the use of appliances, plug loads and home electronics expands in the EU.

5. Conclusions

We describe a comprehensive energy simulation and cost optimization model that is a useful means of finding cost-effective nearly zero energy buildings. To illustrate results, we provide examples of the calculation method carried out in a new residential building prototype in different climates. We show that it is possible to reach a very low energy design in new buildings with source energy savings approximately between 90% and 100% or beyond. However, the way in which this achievement is accomplished at the lowest cost varies by location.

Whether the optimal path emphasizes or not thermal improvements are strongly dependent on the relative heating load in a given location. 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 4.0 kWp 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 71% in Milan. 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 locations.

Results have shown slightly different optimization results between cold and cloudy locations, such as Brussels, Belgium 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.

We also examined how excluding appliances and lighting from the optimization process, as currently allowed in the 2010/31/EU approach, impacts results. We have found such an oversight greatly reduces savings, particularly for electricity, and increases the cost for achieved reductions. Accordingly, we recommend that the optimization process includes lighting and appliances. This inclusion becomes ever more important with future growth in home appliances and electronics grows and associated greenhouse gas emissions.

Finally, we performed a sensitivity analysis where we assumed that the real cost of installed PV systems was roughly twice current costs to account for the need for short term electrical storage to put generation energy on a similar capability to that of efficiency. Doing so showed, indicated insulation and air tightness levels similar in keeping with the Passivhaus approach in colder climates, although still with some larger differences in milder Mediterranean locations. We further note that not only are the costs of installed PV dropping rapidly in the EU, but also the costs of effective electrical storage. This tends to make our assessment in this report conservative and tilted towards efficiency improvements relative to the lowest cost means to reach nZEB levels in new European construction.

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