FLORIDA SOLAR ENERGY CENTER®

Creating Energy Independence

Energy and Economic Optimization to Achieve Near Zero Energy Homes in Europe: Implications of Inclusion of Lighting and Appliances

FSEC-PF-455-13

September 11 – 13, 2013

Published in:

Proceedings of the 7th International Conference on Energy Efficiency in Domestic Appliances and Lighting

Coimbra, Portugal

Authors:

Danny S. Parker, Philip Fairey, Andreas H. Hermelink

1679 Clearlake Road
Cocoa, Florida 32922, USA
(321) 638-1000
www.floridaenergycenter.org

A Research Institute of the University of Central Florida

Disclaimer

Energy and Economic Optimization to Achieve Near Zero Energy Homes in Europe: Implications of Inclusion of Lighting and Appliances

Danny S. Parker, Philip Fairey, Andreas H. Hermelink
Florida Solar Energy Center, Ecofys GmbH

Abstract

Achieving annual net zero energy use in homes has been demonstrated as feasible in dozens of monitored projects in the United States.[1] In particular, very low energy use homes in Europe have been proven within the *Passivhaus* approach.[2] Achieving "nearly zero energy buildings" (NZEB) has also been established as a vital objective over the next decade within the European Union (EU) (Boermans et al., 2011). However, reaching this result at the lowest possible cost remains a key challenge around the world. Balancing renewable power generation with energy efficiency will be vital in Europe as anticipated by Voss, Musall and Lichtmeβ.[4] We describe new energy optimization software, *EnergyGauge: CostOpt* developed to address this need. The model performs detailed hourly sequential simulations showing how to achieve very low or zero energy home designs at the lowest possible cost in a variety of climates. The model can be used either for optimization of new or existing homes, which often have very different costs for various envelope measures. We have adapted the model to run in European climates and demonstrate it here simulating existing homes in 31 representative locations. A key result of our investigation is that energy reductions of 70-100% are economically feasible for existing EU residences. Finally, we illustrate how exclusion of lighting and appliances results in sub-optimal solutions, particularly for electricity use which has a disproportionate impact on greenhouse gas emissions. The results have important implications for the NZEB target established by the EU.

Building Energy Simulation and Optimization Model

The calculation model in *EnergyGauge* is rigorous, using the powerful hourly energy simulation, DOE-2.1E developed by the Lawrence Berkeley National Laboratory.[5] This model estimates household heating, cooling, water heating and appliance loads by each hour. Fundamental building thermodynamics are estimated via transfer functions using a multi-zone representation. A variety of fuels can be simulated. The simulation has been indexed to real buildings to verify its potential to replicate measured energy use in cold versus hot climates.[6] The simulation model has been adapted to run in European climates by adding the needed hourly IWEC weather data files, converting to metric inputs and modifying cost data into a Euro format. Using similar inputs, favorable comparisons have also been produced against the Passivhaus Planning Package (PHPP) software.[7] The economic optimization method is consistent with established procedures for Nearly Zero Energy Buildings in the EU (OJ C 2010/31/EU).

For use with the optimization, we developed nearly one hundred energy conservation measures (ECMs) including insulation, window types, air tightness, heating, cooling, water heating, appliances and lighting. This includes a comprehensive cost database with measure characteristics, life, operation and maintenance and cost. Renewable energy production is evaluated using a photovoltaic (PV) simulation (PVFORM) and a prediction of solar water heating performance based on hourly correlations to the TRNSYS model. 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 least cost path to near zero energy. Even in cold climates, this method may offer some advantages against the more standard *Passivhaus* approach as it is may be possible to reach zero energy performance at similar cost.[8]

The optimization model evaluates the entire suite of options (typically 50-100 measures), selects the option with the highest benefit to cost net present value ratio (termed the Saving to Investment Ratio or SIR), incorporates this option, and then re-simulates all available options. The process continues in this manner until an SIR or 1.0 is reached or until zero energy is achieved using PV resources.

Within our example, an existing home in poor condition is optimized for Berlin, Germany, selecting from available ECMs. The simulated energy demand from each fuel along with the cost data are used to analyze the cost effectiveness of individual measures using the SIR metric. For existing homes, the analysis can consider two different scenarios: a) outright retrofit of existing components and equipment at full cost or b) incremental cost at time of natural replacement.

The cost effectiveness calculations are based on the present value of the life-cycle costs and benefits of the measures over an analysis period of 30 years. The procedures for estimating the life cycle cost calculations are well documented.[9] The assumed economic parameters for the example analysis are shown in Table 1 are based recommended guidelines supplementing Directive 2010/31/EU. The assumed costs, service lives, and maintenance fractions for each of the 75 considered retrofit measures considered are given in an easy to alter Excel spreadsheet which feeds the simulation. The analysis can conducted assuming that retrofit measures are purchased either outright, or through financing, the period of which can be varied. The assumed economic evaluation rates for the calculations presented here are given in Table 1 below as consistent with suggested macroeconomic trends.[10] The value for 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.

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	€0.26/kWh
Current Natural Gas Price	€17.70/ GJ

The physical building and economic parameters are easily modified for analysis; adding measures or combinations of measures to the library is straightforward. Depending on climate and building efficiency starting point, approximately 250-500 simulations with 5-25 iterations are required to reach the optimal set of building characteristics. A complete optimization takes approximately one to two hours on a desktop computer.

Example Results: Optimization of an Existing Home in Berlin

We illustrate the optimization approach for Berlin in a very poorly insulated existing 150 m^2 home loosely based on the prototype description in a recent study by Ecofys GmbH and the Danish Building Research Institute.[3] Fundamental characteristics are summarized in Table 2.

Table 2. Characteristics of Poorly Insulated Home for Optimization Example

House Size	150 m^2 over 2.5 m unheated cellar
Windows	23 m^2 double clear glass with significant air leakage (~3.0 W/m^2K)
Walls	Un-insulated frame walls (~2.8 W/m^2K)
Attic	R-3.3 existing insulation (~0.25 W/m^2K
Doors	Un-insulated wood entry door (~2.8 W/m^2K)
Air Leakage	Very leaky (8 ACH @ 50Pa blower door pressure)
Heating	Hydronic natural gas heating system,75% efficiency
Cooling	COP 2.9 mini-split cooling system in climates requiring cooling (not in Berlin)
Settings	20^{o}C for heating, 18^{o}C from 11 PM to 6 AM daily; cooling 26^{o}C
Hot Water	155 l poorly insulated hot water tank in cellar providing 150 l per day @ 55^{o}C
Appliances	Standard clothes dryer, washer, dishwasher, televisions etc.
Lighting	85% incandescent lamps (15% fluorescent)

The inefficient baseline existing home is predicted to use 3,853 kWh per year and 125 GJ of natural gas for space and water heating and cooking (space heat is approximately 100 GJ). For our initial analysis, cost data is based on a database of the cost of various efficiency measures developed by the U.S. National Renewable Energy Laboratory and converted to Euros (http://www.nrel.gov/ap/retrofits/about.cfm). This was refined by review of costs in Europe for various components and equipment.

Rather than regional prices for electricity and fuels, for this evaluation we use a consistent price so that climate-related differences are highlighted. Representative energy costs for electricity and natural gas were taken from the Eurostat website (http://epp.eurostat.ec.europa.eu/). As such, the analysis presented here is more illustrative of the method and approach, rather than a definitive evaluation for specific locations.

No financial incentives were assumed for either efficiency or renewable energy sources so all can be evaluated on a fair playing field. However, differing measure life is specified for each measure. For instance, most insulation measures are assumed to last at least 50 years as opposed to renewable energy systems which might last 20-30 years and require operation and maintenance during that time and replacement before the end of the analysis period. A key leverage point in the analysis is that if 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.

The final selected options comprise insulating the un-insulated walls to R-2.3, improving ceiling insulation to R-8.6, insulating the cellar on the interior, a better insulated entrance door, substantially reducing building air leakage, a 96% efficiency fully condensing gas boiler and with improved pipe insulation, modern hot water saving plumbing fixtures,100% efficient lighting and an energy efficient clothes dryer. After the measure selection, a 4 kW grid-connected PV system is installed that more than produces all the electricity needed by the site.

Our example analysis shows the capability to achieve approximately an 80% energy savings in Berlin with cost effective retrofits at a lower cost than the current building, paying for energy costs without the improvements. The measures selected were as follows:

Table 3. Selected Order of Measures for Berlin Optimization Example

Code	**Description**
AirSealing	Building air leakage reduced from 8 ACH@50Pa to 4 ACH
FrmWR-2.3	Insulate un-insulated wall cavities to R-2.3 (drill & fill system)
CeilR5.3	Increase ceiling insulation level from R-3.3 to R-5.3
CeilR6.7	Increase ceiling insulation level from R-5.3 to R-6.7
Pipeins	Insulate exposed hot water piping in the cellar (R-1)
LowFlSho	Change plumbing fixtures to modern low flow fixtures
InsDoor	Retrofit existing un-insulated door to R-1 insulated model
BsmtWR3.3	Retrofit R-3.3 insulation to the interior of the cellar walls with finished wallboard
Tighter	Building air leakage reduced from 4 ACH@50Pa to 3 ACH
CeilR8.6	Increase ceiling insulation level from R-6.7 to R-8.6
100% Lights	Convert all interior lighting to compact fluorescent or LED sources
Ef_Dryer	Install Class A heat pump clothes dryer
Eff Washer	Add Class A energy efficient clothes washer
Boiler-96%	96% efficient condensing boiler installed
4kW-PV	Add 4 kW_{dc} roof-top photovoltaic system with 95% efficiency inverter

The selected package of measures in the example had a total costs of €28,050 of which the turnkey 4-kW PV system was €14,700. The efficiency improvements reduced household natural gas use by 61% (125 to 49 GJ annually) and electricity consumption by 33% (3,853 to 2,599 kWh/yr). After the efficiency improvements, a 4 kW PV system is able to produce more electricity (3,684 kWh/yr) than the improved home uses annually.

The combined total annual source energy required, considering both efficiency improvements and renewable power generation, is cut by 77% resulting in a reduction in annual CO_2 emissions from the household of approximately 7 metric tonnes.

It should be noted that, the cost of improving existing buildings can be much greater than for new ones for certain building elements such as walls, air sealing and elimination of thermal bridges. To the extent that the cost data base reflects these differences, the selection by the optimization model will be dramatically different for new buildings which will typically more resemble *Passivhaus* levels of air tightness and insulation in Europe. Figure 1-3 detail the results of the optimization as sequential measures are selected for the example retrofitted house.

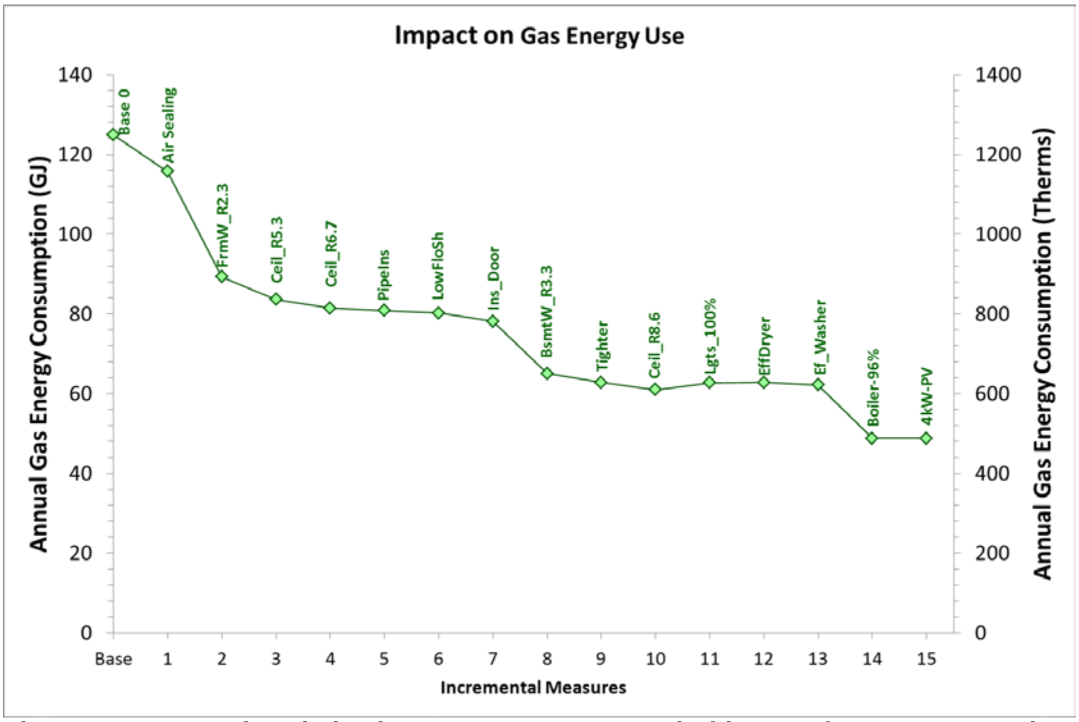

Figure 1. Impact of Optimization Measures on Household Natural Gas Consumption

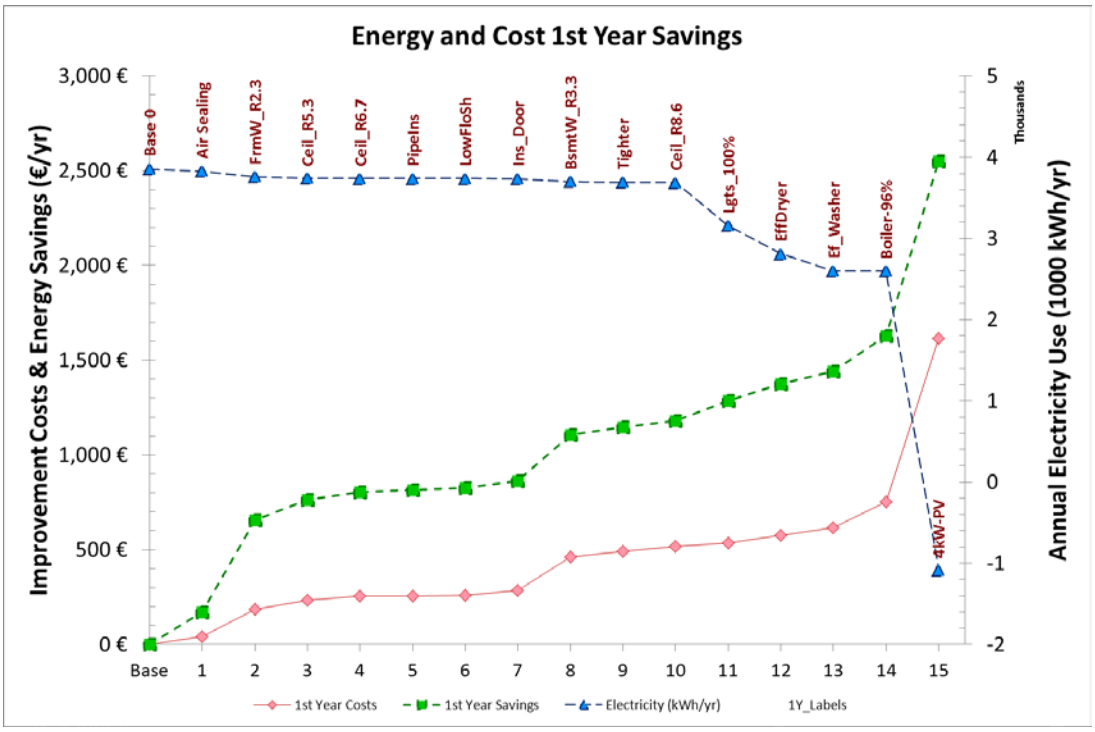

Figure 2: Impact of Optimized Measures on Electricity Use and First Year Annualized Costs

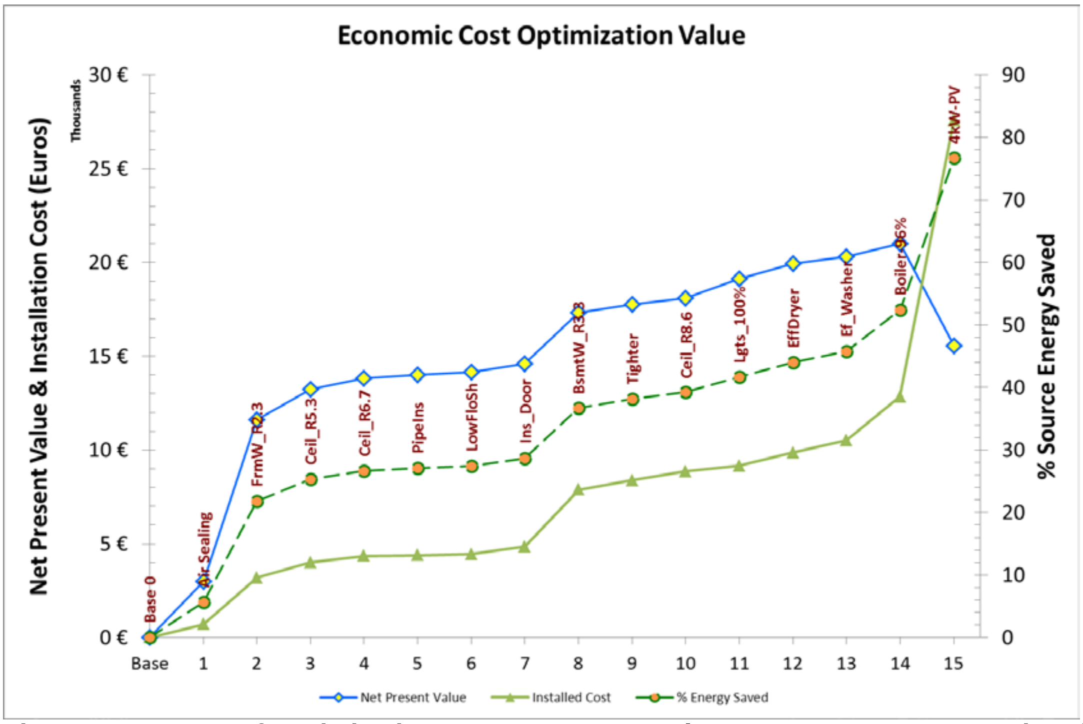

Figure 3: Impact of Optimization on Net Present Value, Percent Energy Saved and Installed Cost

Sensitivity of Optimization Results to Climate

The above analysis was duplicated with the same building and assumptions in Madrid, Spain. In that sunny location, the 4-kW PV system shows much greater output (6,096 kWh/year). Also, the home itself shows greater electrical loads due to cooling- 4,990 kWh which are cut by installed efficiency measures to 3,303 kWh—a 34% reduction. With Madrid's milder weather, gas consumptions starts out at 70 GJ and is reduced by 56% to 31 GJ. The final selected options were similar to those selected for Berlin although with less emphasis on air tightness—a reflection of the milder climate.

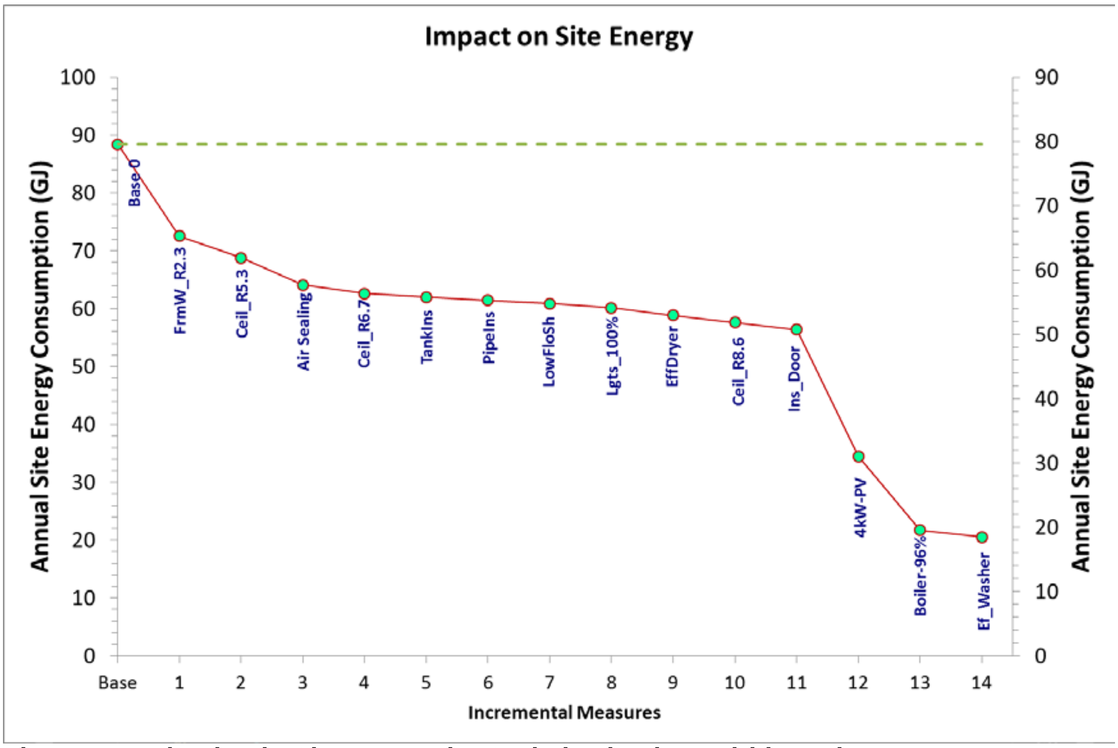

Figure 4: Reduction in Site Energy by Optimization in Madrid, Spain

Total source energy and associated emissions in Madrid are reduced by 100% at a cost of the full package of measures of €24,100. Figure 4 above shows the results in terms of the reduced site energy. There are also financial advantages. The homeowner annually saves approximately €1,288 the first year even after accounting for interest expenses.

It should be noted that including a PV system in the analysis can truncate efficiency measures which are less cost effective than generating the same savings from the solar system. Although not shown here, an optimization for Rome, Italy shows less ceiling insulation and air tightness justified beyond that in Berlin before installing the PV system, because of increased solar electrical output and milder heating-related consumption. Similarly, the same evaluation for Oslo, Norway or Tampere, Finland justifies greater insulation efficiency levels due to the extreme climate and lower PV output.

Table 4 shows the comparative predicted energy use for the unimproved prototype building along with the PV output from the 4 kW PV system as well as the optimized near zero energy building in 31 selected European locations. Although the building stock, appliance saturation and fuels used vary by location (for instance most Norwegian homes are electrically heated due to low-cost hydroelectric power), such evaluation gives an idea of the physical influences of climate severity against the solar PV resource.

Table 4: Predicted Initial Electricity, Natural Gas and PV electric output in 31 Locations for Base and Optimized Near Zero Energy Buildings in 31 Locations

IWEC Location	-------Base Building------		-----Optimized Near Zero Energy Building-----			
	Annual Electricity (kWh)	Annual Natural Gas (GJ)	Solar PV† (KWh)	Annual Net (kWh)	Natural Gas (GJ)	Source Savings (%)
Amsterdam, NLD	3,833	118	3,724	-970	44	79%
Athens, GRC	5,896*	46	6,170	-2,006	20	102%
Berlin, DEU	3,853	125	3,684	-1,084	49	77%
Bremen, DEU	3,875	134	3,608	-796	51	76%
Brussels, BEL	3,830	116	3,361	-597	45	76%
Copenhagen, DNK	3,897	143	3,792	-733	55	75%
Debrecen, HUN	3,829	115	4,711	-1,947	45	85%
Frankfurt, DEU	3,383	118	3,873	-1,195	46	79%
Köln, DEU	3,833	118	3,587	-823	45	78%
Geneva, CHE	3,810	108	4,410	-1,665	42	84%
Hamburg, DEU	3,868	131	3,604	-787	51	76%
Kiev, UKR	3,895	141	4,633	-1,565	56	79%
Linz, AUT	3,858	127	4,153	-1,344	50	79%
Lisbon, PRT	4,247*	39	6,301	-3,402	20	120%
London, GBR	3,810	109	3,832	-1,105	40	81%
Madrid, ESP	4,990*	70	6,096	-2,793	31	100%
Moscow, RUS	3,976	172	3,732	-782	43	84%
Munich, DEU	3,887	138	4,248	-1,296	54	78%
Oslo, NOR	3,940	158	3,438	-429	50	78%
Paris, FRA	3,798	104	3,941	-1,215	40	82%
Palermo, ITA	5,756*	28	6,304	-2,276	14	111%
Prague, CZE	3,904	145	3,523	-565	44	80%
Rome, ITA	4,785*	52	5,562	-2,630	25	103%
Salzburg, AUT	3,851	124	3,987	-1,190	49	79%
Seville, ESP	6,139*	32	6,576	-2,514	15	113%
Sofia, BGR	3,829	115	4,013	-1,246	44	80%
Stockholm, SWE	3,949	162	3,664	-656	47	81%
Stuttgart, DEU	3,851	125	4,139	-1,352	47	79%
Tampere, FIN	4,017	188	3,680	-913	46	85%
Vienna, AUT	3,846	122	4,223	-1,429	47	81%
Warsaw, POL	3,896	141	3,782	-834	40	82%

*Assumes cooling system is available in these locations
†Annual output of 4 kW_{dc} photovoltaic system on unobstructed south-facing roof

If it is not desirable to judge efficiency versus renewable generation, alternate results can be obtained by deleting the PV system. Similarly, it is possible to optimize a building with no heating and/or cooling equipment upgrades available to assess the optimal building shell improvements alone. Although the EU specifies 30 years for this type of analysis, it can be argued that 50 years would be a more representative time line as many important options, such as higher levels of insulation, have very long life relative to shorter lived options. Finally, as the model has hourly output, it is possible to directly assess predicted winter and summer peak impacts of selected measures along with that of the PV element.

Influence of Incremental Measures on Optimization Results

Using the optimization model, it becomes apparent that the ratio of initial measure expense to energy savings level largely governs the resulting series selection. Service life is also a factor. This indicates the need to collect the most representative European cost data for use with future optimization.

Within an incremental analysis, also becomes clear that measures which are at the end of their useful lives are very often selected whereas they are not chosen in the "outright replacement" paradigm. This is because the cost for outright replacement to the most efficient appliance is often much greater than the incremental cost to choose the same efficient model over the standard one when it is worn out.

For instance, in the example given, if it is indicated that the heating system, dishwasher, clothes washer and refrigerator are all needing replacement, the optimization will readily choose the most efficient models for these (for instance the *Top-Runner*, or *A++* models) within the optimization whereas they are not selected otherwise.

The concept of an incremental evaluation has important implications for retrofitting existing buildings where a building-specific audit to evaluate remaining appliance and building component life may positively influence the savings potential. Based on an incremental analysis for Berlin in Figure 5, replacement of worn out windows, efficient washers, dishwasher and a more efficient heating system results in 11 GJ of additional site energy savings and 92% overall source energy savings at a lower total cost (€24,800). The same type of analysis conducted in Madrid also selected the better appliances, but improved the cooling system on replacement and also achieved more than a 100% reduction to annual source energy demand even with a smaller 3 kW PV system.

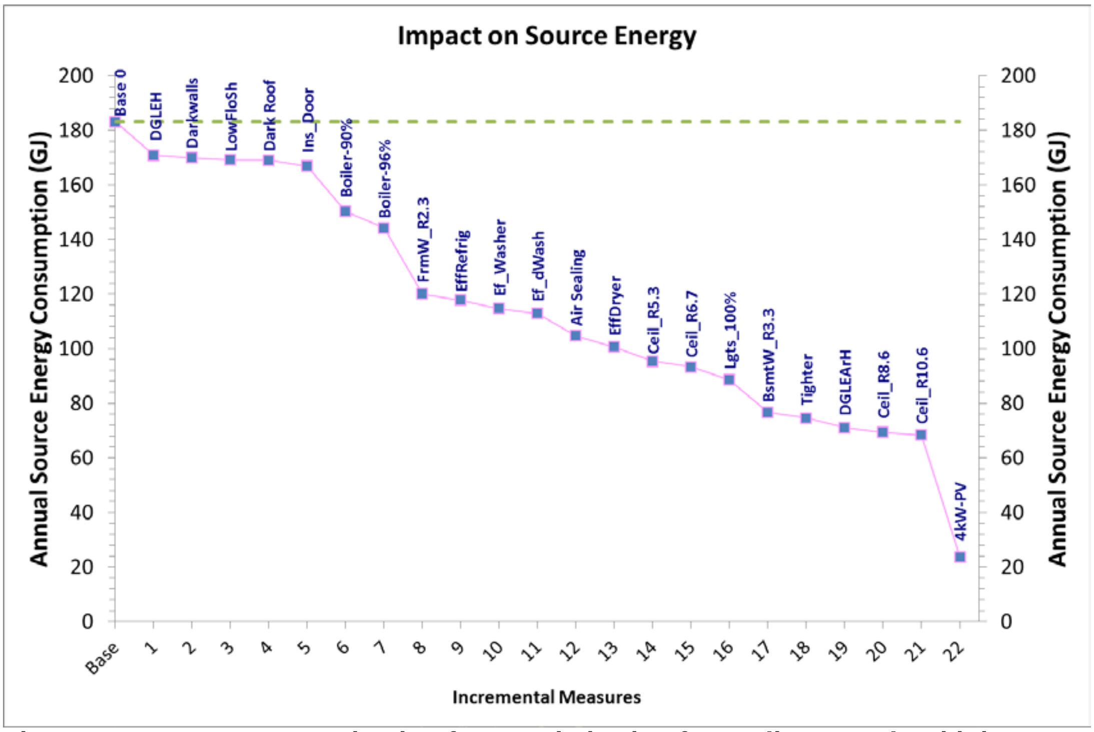

Figure 5: Source energy reduction from optimization for Berlin example with incremental costs for measures.

This approach may argue for a two-tiered analysis: one for of items that should be improved right away, along with another evaluation of those that should be upgraded to best technology at the time they reach the end of their service life.

Impact of Not Considering Appliances and Lighting in the Optimization

The current approach for locating optimal paths for achieving near zero energy buildings in the EU does not require the energy use in appliances and lighting be considered in the optimization process.[11] However, our results indicate that exclusion serves to limit achieved energy savings—particularly for electricity—and would require increase to more expensive photovoltaics to reach similar reduction levels. This is particularly true in the case of lighting where the economic advantage of CFL and LED lighting is very compelling for retrofitting existing homes.

To illustrate, we performed the same optimization analysis for Berlin and Madrid when appliances and lighting options are not available within the optimization. Achieved energy savings are lower in both locations. For the same prototype, source energy reductions are lowered from 77% to 71% in Berlin and from 113% to 93% in Madrid. In particular, not including lighting and appliances leads to compromised electricity efficiency. In Berlin eliminating lighting and appliances from consideration results a loss of economic savings of 1,311 kWh/year. This could be offset by more PV, but at a higher incremental cost. Results also showed the importance of considering appliance and lighting energy is progressively more important in warmer climates where lower internal heat gain levels can reduce potential space cooling.

Our results clearly indicate that including appliance and lighting energy in the optimization process is important to achieve nearly zero energy buildings at the lowest possible incremental cost. Moreover, this inclusion will likely become more important as the growth in home appliances and electronics continues to expand in the EU.

Summary

We describe a comprehensive energy simulation and cost optimization model that is a powerful means to find the least cost approach to achieve nearly zero energy homes. *EnergyGauge Costopt* consists of a detailed energy simulation, a detailed economic evaluation calculation and powerful optimization model. It is possible to evaluate both new and existing home designs and to consider how component remaining life influences the optimal choices for house retrofits.

We provided an example of the calculation method in action for a poorly insulated existing home in Berlin, Germany and Madrid, Spain. Parametric studies have also been completed for other European climates. We show it is possible to reach a very low energy design in existing homes with approximately a 75% - 100% source energy savings (and similar greenhouse gas reductions) at the lowest cost through using a combination of better insulation, windows, building tightness as well as improved Energy efficient Class-A appliances, lighting and home energy management systems along with a 4 kW PV system. In both locations, optimized building has less than zero net electricity consumption on an annual basis and natural gas consumption for space heating and water heating is reduced by 56% in Madrid and 61% in Berlin. However, the achievement of net electricity neutrality is only achieved if home lighting and appliances are optimized at the same time that the building “technical” systems are addressed.

While we provide a conservative economic assessment above, it is possible to alter the inputs to consider very long time horizons and/or higher energy inflation rates. The optimization can also be limited to only non-equipment related options, providing best evaluation of one-time opportunities such as building component insulation levels. It may be advisable to perform this type of optimization first since one can argue that heating, cooling and appliance systems are renewed several times during a building’s life, whereas the envelope measures are in place for a long time with few points of possible intervention.

Using the model, we somewhat different optimization results between cold and cloudy locations, such as Berlin and sunny ones, such as Madrid. For instance, in the warmer locations, interior appliance efficiency measures are selected earlier as heating loads are not as significantly increased, and in the case of the warmest locations—cooling loads may be reduced. In colder climates, insulation and building tightness appear most important.

Such an analysis method can provide important input on how to achieve very low or zero energy homes in the European climate at the lowest possible cost. This methodology may augment the efficiency-only *Passivhaus* approach since renewable energy resources can be fairly evaluated against incremental building improvements. Similarly, important building thermal improvements are not shortchanged since the differing lifetimes of insulation, equipment and renewable energy systems can be fully taken into account within a balance approach.

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

Acknowledgements

Thanks to Kjell Bettgenhaüser with Ecofys for assistance collecting cost and performance data. Brian Hanson made necessary adjustments to the simulation software coding and translation of hourly weather files. Justin Khan automated the output plotting process.

References

[1] Parker, D., “Very Low Energy Homes in the United States: Perspectives on Performance from Measured Data,” prepared for National Academy of Sciences, Energy and Buildings, Vol. 41, Issue 5, May, 2009.

[2] Schnieders, J. “CEPHEUS: Measurement Results from more than 100 Dwelling Units in Passive Houses,” Proceedings from the ECEEE 2003 Summer Study, European Council for an Energy Efficient Economy, Saint Raphael, France.

[3] Boermans, T., Hermelink, A., Schimschar, S., Groezinger, J., Offerman, M., Thomsen, K.E., Rose, J. and Aggerholm, S., Principles for Nearly Zero Energy Buildings, ECOFYS, and the Danish Buildings Research Institute, Buildings Performance Institute, Brussels, November, 2011.

[4] Voss, K. Musall, E. and Lichtmeβ, M., 2010. “From Low Energy to Net Zero Energy Buildings: Status and Perspectives,” Journal of Green Building, Vol. 6, No. 1.

[5] Parker,D., Broman, P., Grant, J., Gu, L., Anello,M., Vieira, R. and Henderson, H., "*EnergyGauge USA*: A Residential Building Energy Design Tool." Proceedings of Building Simulation '99, 6th National International Building Performance Simulation Association Conference, Texas A&M University, College Station, TX, September 1999.

[6] Fuehrlein, B., Chandra, S., Beal, D., Parker,D. and Vieira, R., "Evaluation of EnergyGauge® USA, A Residential Energy Design Software, Against Monitored Data." Proceedings of ACEEE 2000 Summer Study, pp 2.115 - 2.126, American Council for an Energy Efficient Economy, Washington, DC, August 2000.

[7] Feist, W., Pfluger, R., Kaufmann, B., Schnieders, J., Kah, O., Passivhaus Projektierungs Paket 2004, Passivhaus Institut Darmstadt, 2004

[8] Straube, J. “The Passive House Standard (Passivhaus): A Comparison to Other Cold Climate Low Energy Houses,” Building Science Corporation, BSI-025, Somerville, Massachusetts, September 2009.

[9] Brandemuehl, M. and Beckman, W., “Economic Evaluation and Optimization of Solar Energy Systems,” Solar Energy, 23 (1), 1979.

[10] European Union, 2010. “EU Energy Trends to 2030: Update 2009,” Luxembourg, August, 2010.

[11] European Union, Official Journal, “Directive 2010/31/EU of the European Parliament and the Council of 19 May 2010 on the energy performance of buildings.” L 153/13. Also, EU No. 244/2012 of 16 January 2012: “Framework for calculating cost optimal levels of minimum energy performance…” and 2012/ C 115/10, “Guidelines…”