FINANCIAL VIABILITY OF ENERGY EFFICIENCY MEASURES FOR SINGLE-FAMILY HOUSES IN THREE URBAN AREAS OF EUROPE

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Abstract

The financial viability of energy efficiency measures for single-family houses in three urban areas of Europe, each having different climatic conditions, building codes and energy prices, were investigated in this paper. Athens, Copenhagen and Stuttgart were selected for the purpose of the task. The energy efficiency measures are: upgrading of building thermal insulation and air-tightness, use of energy efficient windows instead of standard windows and installation of a mechanical ventilation heat recovery (MVHR) system. Present building codes, energy prices and economic parameters were incorporated in a computer code with hourly weather data of the selected locations. The level of financial viability for the specific energy efficiency measures is assessed through the net present value (NPV), the savings to investment ratio (SIR) and the payback period for the incremental costs.

The existing building codes in Copenhagen are very strict and the single-family house, upgraded to passive house levels, could gain modest financial savings only in case of gas or oil heating. The price of district heat and its annual inflation rate are relatively low, thus no energy improvements with positive financial balance are possible. In Stuttgart, where the single-family house complies to less severe building codes, basic energy efficiency measures present more attractive SIR values and shorter payback periods, especially in case of oil-heated houses. Advanced upgrades, such as a 90% efficient MVHR system combined with passive house thermal insulation and air-tightness, are financially viable only in oil-heated houses and in case of a 10% oil price inflation rate. In this case, the corresponding incremental cost of about 26 000 € is repaid through energy savings after 22 years, yet the payback period and the overall financial viability of the energy efficiency measures depend largely on future energy price. Codes for the energy performance of building are lenient in Athens, therefore both basic and advanced energy efficiency upgrades are financially positive, even for a wide range of values of costs of capital and energy prices inflation rates. In Greece, the present oil price (0.127 €/kWh) is nearly equal to the price of electricity (0.13 €/kWh), thus an effective cash saving action would be the installation of an air-to-water heat pump instead of a common oil boiler.

1. Introduction

In 2010, the recast of the Energy Performance of Buildings Directive (Directive 2010/31/EU) set new, very strict targets regarding energy efficiency for new buildings in the EU. The Directive wants Member States to ensure that all new buildings in the EU are nearly zero energy buildings by December 31, 2020 as well as that new buildings occupied and owned by public authorities are nearly zero energy buildings after December 31, 2018. These new buildings, being virtually zero energy consumers, will eventually affect positively the EU-27 energy dependency which peaked a concerning 54.8% in 2008 (Eurostat, 2010a). Households and services, transport and industry are the major energy consuming sectors, being at the same time the largest potential energy saving sectors (Eurostat, 2010b).

Households (services excluded) consume 25.4% of the overall final energy in the EU. Furthermore, services and households together account for 40.8% of the final energy consumption in the EU (Eurostat, 2010a). Apart from constructing new highly-efficient buildings, refurbishment and retrofitting of old buildings and houses presents a significantly greater opportunity for energy savings in the household sector. Also, Member States should define minimum requirements for the energy performance of buildings with the aim of achieving cost-optimum between initial investments and energy expenditures throughout the building lifecycle. Member States can define minimum requirements that are more energy efficient than cost-optimal energy efficiency levels, but if the opposite occurs, the discrepancy should be justified or appropriate steps should be taken in order to reduce the difference.

Single-family houses (including two-family houses and row houses) account for the 50% of the 207 million households in the EU (Nemry and Uihlein, 2008). Single-family houses alone make up about one-quarter of the EU building stock. An average EU household consumes a total of almost 17 MWh of energy per year (Eurostat, 2010a). On the other hand, the average single-family house consumes more energy than the average household both cumulatively and per unit area. Therefore, increasing interest exists for quantifying the financial effects of energy efficiency actions, both for new and old single-family houses.

Nikolaidis et al. (2009) carried out economic analysis of different energy saving measures for the Greek building sector. They concluded that the most effective energy saving investment for an old detached single-family house is upgrading of the lighting, followed by insulation of the building and use of automatic temperature control system. Replacement of windows and doorframes is less cost-effective.

Kragh and Rose (2011) presented an economic overview for refurbishment of single-family houses built in 1920 and 1975 in Denmark. They showed that a wide range of energy efficiency measures have a positive financial balance. Though, they stated that the payback period is very dependent on future energy prices: an assumed future energy price of 0.2 €/kWh could yield significant annual cash savings, but at the present price of 0.1 €/kWh the refurbishment is still economically neutral.

Sadineni et al. (2011) investigated on the economic feasibility of energy efficiency measures for residential buildings in Nevada, USA. Comparisons of energy efficiency houses were made with code-built houses. The authors conclude that basic energy efficiency upgrades, such as improving the lighting, the airtight envelope, or the wall insulation and the windows' quality results with the shortest payback periods. But, advanced energy efficiency measures, a ventilation heat recovery unit for example, are not economically advantageous.

A large number of papers discuss on the economic aspects for the refurbishment of old houses and buildings, yet there are still few papers and researches which address the potential energy saving and financial benefit that arises when constructing buildings with advanced energy efficiency measures instead of complying with codes for the minimum energy performance of buildings and building elements. This paper investigates on the financial viability of several most common energy efficiency measures for single-family houses in three urban areas of Europe: Athens, Copenhagen and Stuttgart. Comparisons were made to code-built houses that satisfy minimum energy performance requirements and have the same general overall characteristics. The considered energy efficiency measures are: upgrading of the level of thermal insulation and building air-tightness, use of highly efficient exterior windows, installation of a mechanical ventilation heat recovery system (MVHR). Different weather conditions, economic circumstances, building codes and energy prices are taken into account to estimate realistically the cost-effectiveness of the energy efficiency measures.

2. The reference single-family house

2.1. Energy consumption of households in Germany, Greece and Denmark

General characteristics and energy consumption in the German, Danish and Greek building stock are listed in Table 1. There are 39.2 million households in Germany (Ò Broin, 2007) and 92.3% of them have a central heating system (HSEU, 2010). About 43% of the German households use natural gas and 32% use heating oil for space heating and hot water supply. District heating, solid fuels and electricity provide space heating in the remaining 25% of the households. On the contrary, a central heating system is installed in 62% (HSEU, 2010), 69.1% according to EPA-ED (2003), of the 4.2 million households in Greece (Ò Broin, 2007). 61.5% of the Greek households use heating oil for space heating, while households with electric and natural gas central heating systems account only for the 3.8% and 2.5%, respectively. EPA-ED (2003) reported also that households with stand alone heating systems most commonly use wood (14.7%), oil (11.2%) and LPG stoves (2.5%). Denmark counted 2.6 million households in 2010, of which 98% have a central heating system (HSEU, 2010). District heating serves 61.3% of the Danish households and covers

49% of the space heating demand in all buildings (EPA-ED, 2003; ENS, 2009; DFF, 2011). In Denmark, 15.1% of the households have natural gas central heating systems (ENS, 2009). Heating oil boilers are installed in 14% of the Danish households, and log wood boilers or electric heating systems in the remaining 9.6% (DEA, 2009; ENS, 2009).

Tab. 1: Characteristics and energy consumption of the building stock in Germany, Greece, Denmark and EU-27

	Germany	**Greece**	**Denmark**	**EU-27**
Number of households[1], million	39.2	4.3	2.6	207
Single-family houses*[2], % of households	46	59	50	50
Average floor area of household[1], m^2	85	82	109	88
Average number of persons per household[3]	2.1	2.6	2.1	2.4
Final energy consumption of households[3], TWh	792.9	59.9	51.9	3450
• As share of total final energy consumption, %	30.4	24.3	28.7	25.4
• Per average household, MWh/household	20.24	13.88	19.91	16.63
- Electricity	3.57	4.21	4.22	3.94
- Heating oil	4.58	7.38	2.96	2.64
- Natural gas	9.58	0.62	3.11	7.20
- Heat	1.18	0.13	6.57	1.08
- Solid fuels	0.22	0.03	0.13	0.48
- Renewables	1.11	1.51	2.92	1.29

Sources: [1] Ò Broin (2007); [2] Nemry and Uihlein (2008); [3] Eurostat (2010a)

* Single-family houses category includes two-family houses and row houses

2.2. The reference single-family house

A computer code is developed to determine space heating and space cooling energy consumption in the reference single-family houses in Athens, Copenhagen and Stuttgart. The weather data are generated from monthly average conditions (SEL, 2011) and include hourly values of global and beam solar irradiation, air temperature and humidity, wind velocity and wind direction. In all the three locations, the reference single-family house has net occupiable area of 150 m^2 in two storeys (building shape factor 0.8) connected with an internal staircase and it is occupied by 5 persons. The reference single-family houses are built by the code, i.e. they comply with local or national codes for minimum energy performance of buildings. Also, the three reference single-family houses have different characteristics because of different climate and housing traditions, Table 2. In Athens, for example, the house has a flat roof and south-facing windows shaded by shutters or roof overhangs in order to reduce solar gains in summer. Final energy consumption for space heating and space cooling in the reference single-family houses are listed in Table 2.

The final energy consumption for space heating is 65.7 kWh/m^2a in the Danish reference single-family house. This number is in accordance with the Danish building regulation which prescribes the maximum final energy consumption, including space heating, cooling, ventilation and hot water supply, to $(70+2200/A)$ kWh/m^2a in residential buildings, where A is the heated floor area (DMEBA, 2008). Among other, the regulation sets the maximum allowable building air leakage to $n_{50} < 2\ h^{-1}$, and in case of a very airtight building ($n_{50} < 1\ h^{-1}$), a mechanical ventilation system with heat recovery at least 65% efficient should be installed.

The German reference single-family house consumes 70.2 kWh/m^2a of natural gas for space heating annually. The EnEv09 German energy saving act for buildings (2009) set new, stricter U-values for exterior building elements and windows. The maximum building air leakage is set to $n_{50} < 3\ h^{-1}$ and a mechanical ventilation system should be used if $n_{50} < 1.5\ h^{-1}$.

In both the Copenhagen and Stuttgart reference single-family house, the space cooling energy demand amounts to only 2 kWh/m^{2}a and indoor air comfort is acceptable without AC cooling. However, if necessary, summer night natural ventilation can cool the house after hot summer days.

The reference single-family house in Athens consumes 51.5 kWh/m^{2}a of heating oil for space heating and 10.1 kWh/m^{2}a of electricity for space cooling (COP = 3.42). Greece introduced stricter energy requirements for buildings in 2010. The building elements *U*-values have strictened and other, previously non-compulsory energy efficiency measures are introduced. Hot water heating, for example, should be at least 60% solar-generated.

Tab. 2: The reference single-family house in Athens, Copenhagen and Stuttgart

	Athens	**Copenhagen**	**Stuttgart**
Basic weather data (SEL, 2011)			
Heating degree-days/Cooling degree-days	1220/1197	3666/138	3024/218
Max/avg/min ambient air temperature, °C	40.4/17.9/-5.2	32.2/8.2/-18.8	32.9/10.2/-15.2
Global solar irradiation, kWh/m^{2}a	1578	1038	1168
Single-family house characteristics			
Net floor area, m^2	150	150	150
Air change rate due infiltration, h^{-1}	0.20	0.15	0.15
External wall/floor/roof *U*-values, W/m^{2}K	0.50/0.90/0.45	0.20/0.15/0.15	0.28/0.35/0.20
Overall window *U*-value, W/m^{2}K	2.00	1.50	1.30
Glass shortwave transmittance, -	0.69	0.63	0.60
Area of windows: south/east/west/north, m^2	10/5/5/7	12/5/5/2	14/5/5/2
Summer overheating protection	Overhang/shutters	-	-
Windows' frame ratio, -	0.30	0.30	0.30
Internal heat sources, W/m^2	3.5	3.5	3.5
Space heating source	Fuel oil boiler	District heating	Gas boiler
Space cooling source	AC unit	-	-
Heating distribution system	Radiant floor	Radiators	Radiators
Cooling distribution system	AC unit	-	-
Fresh air distribution	Natural	Natural	Natural
Natural air change rate*, h^{-1}	0.30/0.50/0.70	0.20/0.30/0.40	0.20/0.30/0.40
Heating/cooling set-point temperature, °C	20/27	20/-	20/-
Final energy consumption			
Space heating, kWh/m^{2}a	51.5	65.7	70.2
Space cooling, kWh$_{el}$/m^{2}a	10.1	-	-

* For the periods: November 1 - March 31/April 1 - May 31 & September 1 - October 31/June 1 - August 31

3. Energy prices and economic variables

3.1. Energy prices

Denmark has the highest domestic natural gas (0.11 €/kWh) and heating oil (0.13 €/kWh) prices in Europe, Figure 1. Heat from district heating grid is cheaper with an average price of 0.10 €/kWh, though the price ranges from 0.05 to 0.15 €/kWh, depending on size of the heat plant, type of primary energy source and supply company (Aronsson and Hellmer, 2009). The present electricity price in Denmark is 0.271 €/kWh. In Greece, starting from 2008 the heating oil price is increasingly more expensive to just about equal the present heating oil price in Denmark. The average electricity price of 0.1282 €/kWh for households is only slightly bigger than the heating oil price (0.127 €/kWh) in Greece during 2011. On the other hand, Germany, where 75% of the households are either supplied with natural gas or heating oil, has average gas and heating oil prices of 0.0581 €/kWh and 0.0816 €/kWh, respectively (Eurostat, 2009). The present electricity price in Germany is 0.244 €/kWh. The average energy prices at national level are taken as reference prices, since very little data on the differences of energy prices within a country are available.

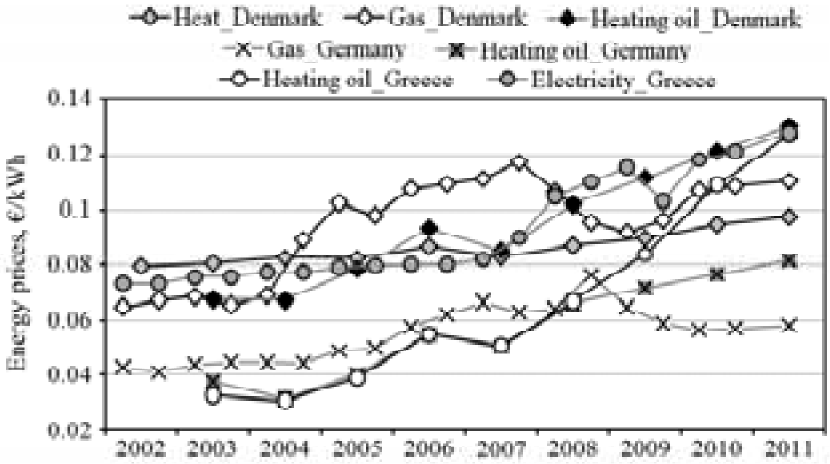

Fig. 1: Fuel and electricity prices for heating of households in Germany, Greece and Denmark

To estimate correctly the financial viability of an energy efficiency measure, energy price inflation rates e(%) need to be assumed. Although energy prices are very sensitive to political, economic, environmental and industrial circumstances, and future energy prices can more or less diverge from predictions, energy prices were increasing in the last decade and most likely will continue to do the same in the future. Once the average energy price inflation rate is determined, future household expenditures on energy can also be predicted. In Denmark, the average price inflation rate for gas is 6.3%, for heating oil 8.5%, and only 2.3% for district heating. In Germany, the price inflation rate for natural gas is 3.9% for heating oil 10.2%. In Greece, the inflation rate for the price of heating oil is an enormous 18.6% while it is 6.4% for electricity.

3.2. Incremental investment costs

The incremental investment cost of an energy efficiency measure is defined as the difference between investment costs in the energy efficiency measure and the investment costs (anyway costs) that occur when purchasing the measure having minimal required level of performance or quality. The incremental costs are the costs that otherwise would not occur in the reference case, but arise when realising a project. The incremental investment costs are defined by

$$C_{\mathrm{I}} = \left(C_{\mathrm{ee}} - C_{\mathrm{ref}}\right)_{\mathrm{i}} \cdot \mathrm{PLI} \qquad \text{(eq. 1)}$$

where C_{ee} is the investment cost for the energy efficiency measure i and C_{ref} the investment cost for the corresponding minimum performing measure. The investment costs in the considered energy efficiency measures were retrieved from various producers and dealers and the data is fitted with curve-fits. The investment cost in thermal insulation (k = 0.04 W m^{-1}K^{-1}) is defined taking into account the surface A(m^2) and the thickness δ(cm) of the insulation

$$C_{\mathrm{t}} = (15 + 1.5 \cdot \delta) \cdot A,\ € \qquad \text{(eq. 2)}$$

The investment cost in energy efficient windows is defined taking into account the U-value (W m^{-2}K^{-1}) and the total surface A(m^2)

$$C_{\mathrm{w}} = 350 \cdot U_{\mathrm{w}}^{-0.75} \cdot A,\ € \qquad \text{(eq. 3)}$$

The investment cost in the building airtight envelope (airtight membrane) is defined knowing the surface and the air-tightness n(h^{-1})

$$C_{\mathrm{m}} = \left[5\left(1.2 - 2 \cdot n\right)^3 + 2\right] \cdot A,\ €\ \ (\text{for } 0.05 \le n \le 0.25) \qquad \text{(eq. 4)}$$

The investment cost in the MVHR system is defined with respect to the fresh air flow rate V (m^3/h) and the efficiency η of the heat recovery unit

$$C_{\mathrm{MVHR}} = 30 \cdot V + 400 \cdot (1-\eta)^{-0.45}, \text{ €} \quad \text{(eq. 5)}$$

The differences in investment costs for energy efficiency measures between Greece, Denmark and Germany are taken into account with the country's price level index (PLI). The PLI is defined as the ratio between purchasing power parity and the current nominal exchange rate (Eurostat, 2011). The PLIs compare average EU-27 (PLI = 1) price levels with Member States price levels. The PLI for household's machinery and equipment category is 1.02 in Germany, 1.11 in Greece and 1.10 in Denmark (Eurostat, 2011).

3.3. Evaluating the financial viability of energy efficiency measures

The net present value (NPV) is the sum of present values of individual cash flows. An investment should be realized if NPV > 0 and between two reciprocally exclusive investments, the one with higher NPV should be selected. Here, the NPV is used to assess the financial viability of different levels of energy efficiency and equipment performance. The NPV is defined with the following expression

$$\mathrm{NPV} = -C_{\mathrm{I}} + \sum_{n=1}^{N} \frac{B_{\mathrm{E}} - C_{\mathrm{M}} - C_{\mathrm{E}}}{(1+p)^n}, \text{ €} \quad \text{(eq. 6)}$$

where B_{E} is the annual cash inflow which reflects energy savings arisen by introduction of energy efficiency measures while C_{M} and C_{E} represent the annual cash outflow or opportunity costs: the former corresponding to maintenance costs and the latter to energy costs that otherwise would not occur in the reference scenario. The cost of capital p is the rate of return that could be earned by investing the capital on the financial market or by deposit on a bank savings account. Two values for the cost of capital are considered here: 4% and 10%. A cost of capital of $p = 4\%$ would correspond to a low-risk financial enterprise, as the one undertaken by an average household's owner. The payback period (PP) is determined from eq. 6, calculating the year n that corresponds to NPV = 0. The annual cash inflow is the cash equivalent of the saved energy, determined by the following expression

$$B_{\mathrm{E}} = (Q_{\mathrm{ref}} - Q_{\mathrm{ee}}) \cdot c_{\mathrm{e}} \cdot e^n, \text{ €} \quad \text{(eq. 7)}$$

where the $Q_{\mathrm{ref}} - Q_{\mathrm{ee}}$ is the saved energy in the single-family house with energy efficiency measures, c_{e}(€/kWh) is the present energy price and e its inflation rate. It is assumed that the cash flows from (eq. 6) occur at the end of each year n. The economic evaluation is performed for a number of years of $N = 30$. In eq. 6, all but maintenance and energy costs for the MVHR system are sunk costs that occur anyway in the reference scenario and thus neglected from the expression.

Besides the NPV, the savings with the incremental investment costs of energy efficiency measures can be compared. The savings to investment ratio (SIR) compares the cash inflow with the cash outflow

$$\mathrm{SIR} = \frac{\sum_{n=1}^{N} \frac{B_{\mathrm{E}}}{(1+p)^n}}{C_{\mathrm{I}} + \sum_{n=1}^{N} \frac{C_{\mathrm{M}} + C_{\mathrm{E}}}{(1+p)^n}} \quad \text{(eq. 8)}$$

When NPV = 0, the present value of cash outflows is equal to the present value of cash inflows, thus the realized savings match the investments and SIR = 1. Among reciprocally exclusive investments, the most cost-effective is the one with the highest SIR.

4. Results and discussion

4.1. Financial viability of energy efficiency measures for single-family houses in Copenhagen

The reference single-family house in Copenhagen consumes 65.7 kWh/m^{2}a of district heat (0.1 €/kWh) for space heating at a total annual cost of 986 Eur. The house has a overall building U-value of 0.25 Wm^{-2}K^{-1} resulting from average wall U-value of 0.18 Wm^{-2}K^{-1} and windows' U-value of 1.5 Wm^{-2}K^{-1}. The code-built house is already an energy efficient one, though it does not reach the Danish class 2 low-energy building level (DMEBA, 2008). Further energy savings may be achieved by improving the thermal insulation and the quality of the windows. The average wall *U*-value is varied from 0.18 to 0.10 $Wm^{-2}K^{-1}$ and the windows' *U*-value from 1.5 to 0.8 $Wm^{-2}K^{-1}$, Figure 2. For an average wall *U*-value of 0.10 $Wm^{-2}K^{-1}$ and a windows' *U*-value of 0.80 $Wm^{-2}K^{-1}$ the space heating energy consumption amounts to 40 kWh/m^2a. The corresponding SIR is only 0.50, meaning that the incremental investment costs are twice the cash value of the saved energy, Figure 2. This lack of manoeuvre space for cost-effective energy savings confirms that the Danish codes for energy performance of buildings fit well present energy prices and their future projections. In Figure 2., the SIR ranges between 0.5 and 1.3 for the reference district-heated single-family house in Copenhagen. These SIR values are disadvantageous for investments in upgraded thermal insulation and window quality.

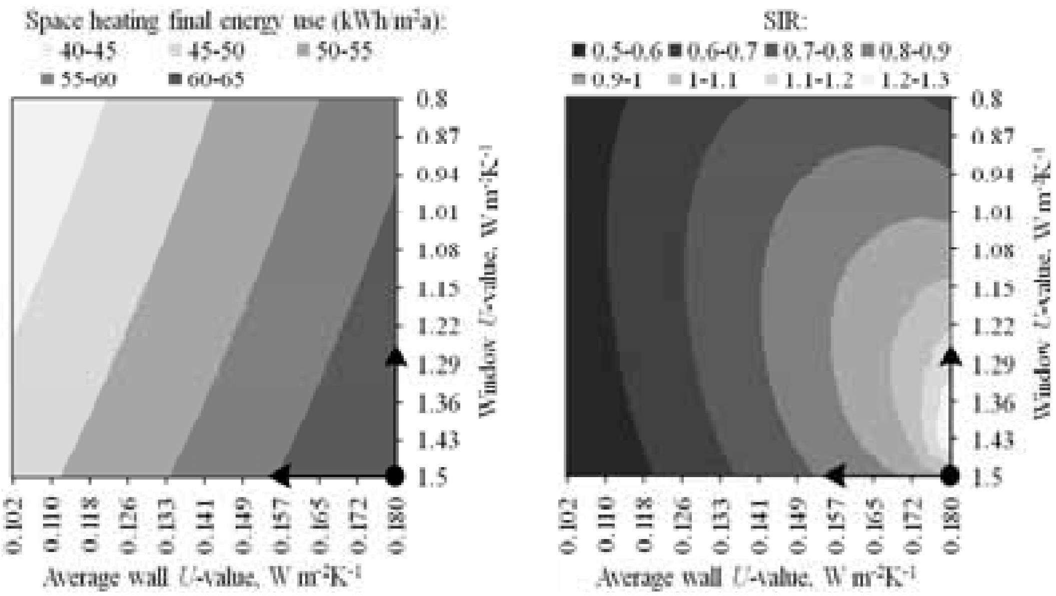

Fig. 2: Upgrading of wall and window *U*-values in the reference single-family house in Copenhagen: effect on space heating energy consumption and SIR values (30 years' period)

Nevertheless, a minor part of the Danish households are heated with gas and oil, which cost 0.11 and 0.13 €/kWh and become more and more expensive at average annual inflation rates of 6.3% and 8.5%, respectively. Hence, the energy efficiency measures are much more attractive for gas- and oil-heated households off the district heating supply grid. Figure 3. compares the NPVs for upgraded single-family houses in Copenhagen having the same overall general characteristics but different heating fuel. The energy efficiency level of the district-heated, gas-heated and oil-heated house corresponds to passive house levels, where all the three houses have an average wall *U*-value of 0.1 $Wm^{-2}K^{-1}$, a window *U*-value of 0.8 $Wm^{-2}K^{-1}$, an air-tightness of 0.05 h^{-1} and a mechanical ventilation system with 90% heat recovery efficiency.

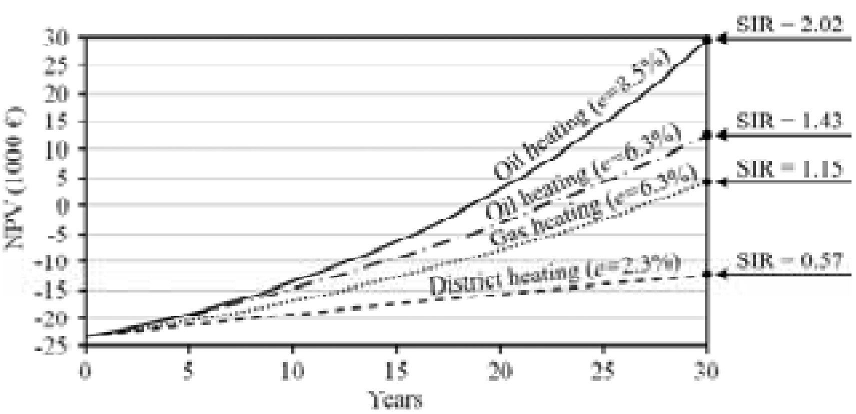

Fig. 3: NPVs and SIRs for three passive-house-performing single-family houses in Copenhagen with different heating fuels

In all the three upgraded single-family houses, space heating consumption amounts to 18 kWh/m^{2}a (within the Danish passive house consumption range), which gains space heating energy saving of 47.7 kWh/m^{2}a. The present cash equivalent of the saved energy is 716 € for district heating, 787 € for gas heating and 930 € for oil heating. But, the MVHR system consumes 620 kWh of electricity, equivalent to a total annual cost of electricity of 168 Eur. All in all, the potential cash savings are especially attractive for gas- and oil-heated houses, as the gas and oil prices inflation rates are much higher than the district heat inflation rate. For heating oil, two price inflation rates *e*(%) are considered: the average 2000-2010 price inflation rate of 8.5% and the average 2000-2010 gas price inflation rate of 6.3%. The incremental investments costs are estimated at 23 400 €. This upgrade is cost-effective in all but the district-heated reference house. In the oil-heated house, the passive house energy efficiency upgrades are repaid in 19 years, assuming an oil price inflation rate of 8.5%, or in 23 years if the oil price inflation rate is 6.3%. The payback period is 27 years in the gas-heated house and would be 100 years in the district-heated house. In other words, households in Copenhagen and generally in Denmark, in view of reaching cost-effective balance between investments and energy expenditures, should be code-built if connection to the local district heating grid is available or built in low-energy or passive house performance levels if gas or oil heating are the only choices.

3.2. Financial viability of energy efficiency measures for single-family houses in Stuttgart

The reference single-family house in Stuttgart consumes 70.2 kWh/m^{2}a of natural gas at a price of 0.058 €/kWh. The annual energy cost for space heating is 612 €, but it would be 907 € in case of oil heating (0.082 €/kWh). The average building *U*-value is 0.34 W m^{-2}K^{-1}, with walls having average *U*-value of 0.28 W m^{-2}K^{-1} and windows of 1.3 W m^{-2}K^{-1}. NPVs resulting from upgrading of thermal insulation and windows as well as from improving the building air-tightness are plotted in Figure 4. Both gas and oil heating are considered. Two fuel price inflation rates *e*(%) are considered: the 2000-2010 average inflation rate of 10.2% and a lower inflation rate of 5%.

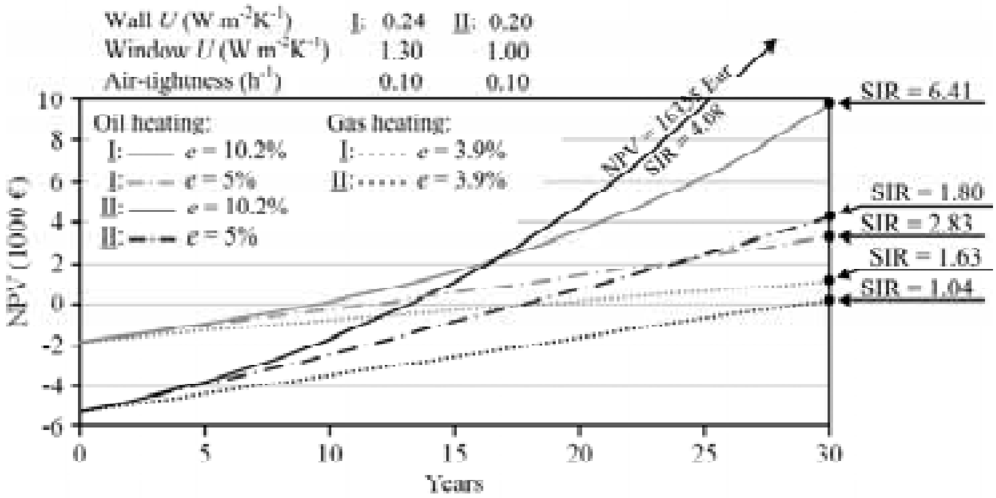

Fig. 4: NPVs and SIRs for two levels of upgrade of insulation, windows and building air-tightness in oil- and gas-heated single-family houses in Stuttgart

Judging from Figure 4. there is space for introducing energy efficiency measures in single-family houses in Stuttgart, at the present German building codes. The German codes for energy performance of buildings are somewhat less severe than the Danish ones, even given the fact that gas and oil prices for households are about 40% lower in Germany. Energy saving measures are cost-effective especially in oil-heated households, even for scenarios when the oil price inflation rate is lower than the predicted 10.2%. In gas-heated houses, improving the average wall *U*-value from 0.28 to 0.24 Wm^{-2}K^{-1} and the building air-tightness from 0.15 to 0.10 h^{-1}, for example, reduces space heating energy consumption by 12% and saves 75 € per year. The incremental investment costs for these energy efficiency measures amount to 1 800 € and are repaid after 18 years. This variant produces 63% more savings than expenditures, thus yielding a SIR value of 1.63. For comparison, the same variant results in SIR = 2.83 if the house is oil-heated. Advanced energy efficiency measure, such as 90% efficiency MVHR system, an average wall U-value of 0.10 $Wm^{-2}K^{-1}$, a window U-value of 0.80 $Wm^{-2}K^{-1}$ and building air-tightness of 0.05 h^{-1}, are cost-effective only in oil-heated single-family houses, Figure 5. Now, the single-family house in Stuttgart consumes only 13 kWh/m^2a for space heating, but for an incremental investment cost of 26 100 €. This set of energy efficiency measures is cost-effective only if the house is oil-heated and if the predicted oil price inflation rate of 10.2% realizes. However, the NPVs, are also significantly influenced both by energy price inflation rates e(%) and costs of capital p(%), for a given fuel type. For oil price inflation rates of 10.2% yearly, the SIR decreases from 1.81 to 0.73 if the cost of capital p is assumed to be 10%, instead of 4%.

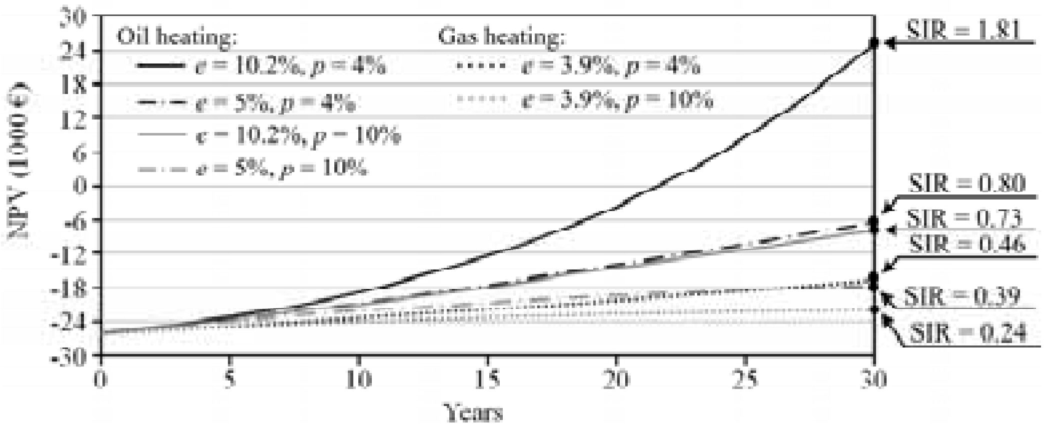

Fig. 5: NPVs and SIRs for upgrading the single-family house in Stuttgart to passive house performance level

3.3. Financial viability of energy efficiency measures for single-family houses in Athens

The reference single-family in Athens encounters quite different circumstances than the ones in Copenhagen or Stuttgart, both climatically and economically. The Greek building codes are more lenient, but heating oil prices are very high, so there should be plenty of space for energy efficiency improvements. Natural gas is still scarcely installed in households which mostly use oil and wood for heating. The average building U-value of the reference single family house in Athens is 0.67 $Wm^{-2}K^{-1}$, where windows should be at least 2.0 $Wm^{-2}K^{-1}$. In the reference house, the annual energy bill for space heating (51.5 kWh/m^2a) is 980 € in case of oil heating, and the bill for space cooling (10.1 kWh_{el}/m^2a) is 194 € for an AC unit having an average seasonal COP of 3.42.

Figure 6. plots the NPVs when introducing basic and advanced energy efficiency measures in the reference house in Athens. The basic upgrades consist of enhancement of the average building U-value to 0.4 $Wm^{-2}K^{-1}$ and building air-tightness to 0.1 h^{-1}. The advanced upgrades consist of further enhancement of the building U-value to 0.25 $Wm^{-2}K^{-1}$, while the building air-tightness remains unchanged (0.1 h^{-1}). The basic upgrades have an incremental investment cost of 5 200 € and cut down space heating consumption to 25 kWh/m^2a. The advanced upgrades have an incremental investment cost of about 12 200 € and furtherly reduce space heating to 14 kWh/m^2a. Space cooling energy consumption in both the basic and the advanced upgrades scenario has not increased at all, in fact it reduced to 9.8 kWh/m^2a, mainly due a well dimensioned roof overhang.

Both basic and advanced energy efficiency upgrades are cost-effective in Athens. Different energy price inflation rates and costs of capital are considered keeping in mind the economic situation in Greece. The average annual heating oil price inflation rate for households is 18.6%, but this value is affected by high taxes and the overall economic situation in Greece. So, to avoid overestimations of the NPV over 30 years, oil price inflation rates of 5% and 10% are chosen instead.

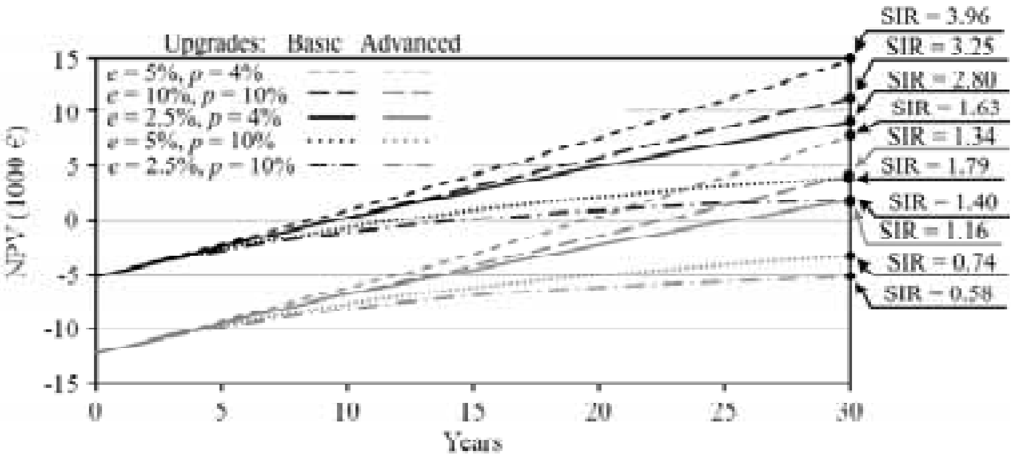

Fig. 6: NPVs and SIRs for upgrading the single-family house in Athens for different annual oil price inflation rates *e*(%) and costs of capital *p*(%)

Looking at the oil and electricity prices in Greece (Figure 1.), and supposing they will remain proportional in the future, a good idea would be to replace the oil burner or electric heaters with an air-to-water heat pump for space heating and cooling. As there is no big difference between oil and electricity prices, a heat pump with HSPF = 9 (seasonal COP = 2.65) would reduce space heating costs by 2.65 times. The investment cost in a 7 kW_{el} ambient air-to water heat pump including fan-coils, piping, other secondary equipment and labour is estimated at 15 000 €, thus replacing the oil burner and the AC unit with total cost of 7 500 €, produces an incremental investment cost of 7 500 € as well. The annual cash savings on space heating would be around 600 €. From here it can be concluded that replacement of the oil heating system and the AC unit with an air-to-water heat pump heating and cooling system is cost-effective in Athens, yet this investment is risky and its cost-effectiveness depends largely on the highly unstable relation between oil and electricity prices in Greece. Indeed, the Greek Federation of Gasoline Station Owners stated its concern about further increases in the heating oil price which could lead homeowners to turn to natural gas, air-conditioning systems or electric heaters instead (Ekathimerini, 2010).

5. Conclusion

In this study, several energy efficiency measures have been financially evaluated for single-family house in Athens, Copenhagen and Stuttgart. It has been concluded that, due to very strict codes for the energy performance of buildings, energy efficiency measures are not cost-effective in district-heated single-family houses in Copenhagen. However, moderate and advanced upgrades could be financially positive in gas and oil-heated households in Copenhagen. Upgrading of an oil- or gas- heated single-family house in Copenhagen to passive house levels of performance would result with incremental investments costs of 23400 € with payback periods of 19 years and 27 years, respectively. And only if the predicted fuel prices inflation rates in Denmark, namely 8.5% for heating oil and 6.3% for natural gas, realize.

In Stuttgart, there is more space for energy efficiency improvements in single-family houses. It has been shown that advanced upgrades, such as 90% efficiency MVHR system combined with passive house thermal protection are cost-effective only in case of oil-heated houses and high oil price inflation rates. The incremental investment costs of about 26000 € are repaid through energy savings after 22 years, yet again the payback period strongly depends on future energy price.

In Athens, both basic and advanced energy efficiency upgrades are financially viable, even for a wide range of values of costs of capital and energy price inflation rates. In Greece, the present oil price (0.127 €/kWh) has almost reached the price of electricity (0.13 €/kWh), thus households' owners could start to replace oil boilers with heat pumps, gas boilers or AC units.

To conclude, out of the three countries, Denmark has the most severe building codes and these are well fitted to cost-optimums between investment costs and energy expenditures throughout the building lifecycle. The German building codes are somewhat less severe than the Danish ones and basic energy efficiency measures are attractive, especially for oil-heated houses. The Greek building codes are the most relax and there are a lot of possible energy efficiency improvements for single-family house in Athens that would yield financially advantageous energy savings, also given the fact that heating oil prices are very high in Greece.

When assessing the financial viability of energy efficiency measures, a number of different variables might or might not influence the final results. The cost of capital, the energy price inflation rates, the initial incremental costs, future energy prices and economic conditions are only the most influential variables. These variables can affect significantly the level of cost-effectiveness of an energy-efficiency measure. Moreover, as the observed time period spans over 30 years. Nowadays and more than ever, it becomes clear that global and local economic circumstances as well as energy prices may change abruptly under remote and apparently innocuous causes. Therefore, it should be kept in mind that the results presented in this paper represent general expectations for the financial viability of energy efficiency measures for single-family houses in locations with different building codes, climatic and economic conditions.

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