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DOI
10.1108/SASBE-04-2019-0044

Publication date
2020

Document Version
Accepted author manuscript

Published in
Smart and Sustainable Built Environment

Citation (APA)
Konstantinou, T., de Jonge, T., Oorschot, L., El Messlaki, S., van Oel, C., & Asselbergs, T. (2020). The relation of energy efficiency upgrades and cost of living, investigated in two cases of multi-residential buildings in the Netherlands. *Smart and Sustainable Built Environment*, *9* (4), 615-633. https://doi.org/10.1108/SASBE-04-2019-0044

Smart and Sustainable Built Environment
doi:10.1108/SASBE-04-2019-0044

The relation of energy efficiency upgrades and cost of living, investigated in two cases of multi-residential buildings in the Netherlands

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Abstract

Decarbonising the housing stock is one of the largest challenges in the built environment today, which is getting the attention not only from policymakers but also from social housing corporations, financial organisations and users. In line with the international Paris-Climate-Change-Conference 2015, Dutch cities and housing associations have embraced this challenge with the ambitions to become carbon neutral in 2050.

To reach such goals, both the rate and depth of renovation need to increase. Several technical solutions to eliminate the energy demand in dwelling have been developed and tested. Nevertheless, the intake rate of deep retrofitting is low. Despite recent developments, there are still significant barriers related to financing, lack of information, and user acceptance.

To address those barriers, the present study sets off to investigate the relationship between energy efficiency upgrades and the cost of living. Focusing on walk-up apartments in the Netherlands, a framework of refurbishment measures that affect the energy efficiency were identified, and their performance was calculated. Furthermore, the rental price adjustment was estimated, taking into account the refurbishment investment and the exploitation cost of the renovated dwellings. The comparison of the energy use and rental price for the different options demonstrated how the different renovation measures affect the energy cost, the energy use, rent and cost of living. The tenants are more likely to accept the solutions that take into account the total cost of living and sustainability benefits. The study gives a holistic standpoint to the issue of energy upgrades, by quantifying the effect of the potential measures for the whole exploitation period. Is has shown the potential of the different interventions to improve the performance and living conditions, without necessarily increasing the total cost of living. Such results aim at supporting the decision-making discussion between the stakeholders, primarily housing associations and tenants.

Keywords: renovation, energy efficiency, total cost of living, decision making, transformation framework, residential buildings

1. Introduction

Decarbonising the housing stock is one of the largest challenges in the built environment today, which is getting the attention not only from policymakers but also from social housing associations and other institutional real estate owners, financial organisations and users. Several studies (BPIE, 2013, BPIE, 2011, IEAAnnex56, 2012, Crawford et al., 2014) have reported that great potential for energy savings, improved health and comfort of the occupants', elimination of fuel poverty, and job creation lay in the technical upgrade of the existing buildings stock. In this context and in line with the international Paris-Climate-Change-Conference 2015, municipalities and housing associations in the Netherlands (AEDES, 2017) have embraced this challenge with the ambitions to become carbon neutral in 2050,

To reach such ambitious goals, both the rate and depth of renovation need to significantly increase (BPIE, 2011, Artola et al., 2016). In the Netherlands, the Energy Agreement for Sustainable Growth

doi:10.1108/SASBE-04-2019-0044

(SER, 2013), indicates that 300.000 dwellings have to be renovated annually to improve the building stock to energy neutrality. This ambition is by the Energy Performance of Buildings Directive adopted by the European Union, which suggests that Member states should specify the expected output of their long-term renovation strategies and monitor developments by setting domestic progress indicators (DIRECTIVE, 2018/844/EU).

Moreover, the Dutch housing associations have the ambition to achieve a carbon-neutral building stock by 2050 (AEDES, 2017). A number of technical solutions to eliminate the energy demand in dwelling have been developed and tested (Sijpheer et al., 2016) (Stroomversnelling, 2013, Konstantinou et al., 2017). Those solution target different levels of energy efficiency, ranging from a small upgrade of the energy label, most commonly up to label B, to achieving zero-energy demand, referred to as “Nul-op-de-meter (NOM) [Zero on the Meter] ”(RVO, 2015).

Nevertheless, the intake rate of deep retrofitting is low. Currently, most improvements in residential buildings consist of basic maintenance and shallow renovation, but broader or deeper energy renovation measures are required (Filippidou et al., 2016). Despite more recent developments, there are still significant barriers related to financing, lack of information, and user acceptance (Matschoss et al., 2013), which keep the rate and the depth of renovation low. The lack of information refers not only to the potential technical solutions but also to the cost-benefit relationship of renovation. Such information is essential for the effective implementation of renovation, as they support the decision making of the stakeholders, including designers, owners and occupants.

Furthermore, the interaction of tenants and owners implies that design and reconstruction will be part of a highly complicated social process and increases the need for design solutions that fit closely with the preferences and means of owners and users in this part of the housing stock. The building’s occupants are becoming, thus, an increasingly important stakeholder during the renovation decision-making, execution and post-renovation stages. Not only do they influence the building energy demand with their behaviour (Guerra-Santin et al., Santangelo and Tondelli, 2017), but they also play a critical role in the decision-making (Abreu et al., 2017), as their agreement is needed before the renovation can take place. In the Netherlands, for example, 70% of tenants in a building must accept the renovation before it can be carried out (BW7:220, 2016). When it comes to accepting the renovation, the residents of the dwellings care less about the technical characteristics of a dwelling, but more about the use, the living expenses, the comfortable and healthy indoor climate, re-dividing and expanding of living spaces, safety, the value of the dwelling, and accessibility (Van der Werf, 2011, Boess, 2015). Financial drivers, such as reduced operational energy costs and potential higher rents and sales for energy efficient homes, are also considered as major inducements towards energy efficiency renovation (Davies and Osmani, 2011). A better understanding of the influence the energy-efficiency measures have on those aspects, and particularly the energy cost savings and the initial investment would support the decision-making and the renovation process. Several studies (Bystedt et al., 2016, Conci et al., 2019, Domingo-Irigoyen et al., 2015, Kumbaroğlu and Madlener, 2012) have been looking at the cost-effectiveness of different measures, as a way to support the decision-making and the business model creation. However, in practice, the cost-effectiveness of measures is not the only decisive factor, as the selection also depends of the feasibility and the project objectives. Moreover, the effect of a cost-effective renovation strategy on the total cost of living of the occupants is not clear.

doi:10.1108/SASBE-04-2019-0044

To this end, the present study sets off to investigate the relationship between energy efficiency upgrade measures and cost of living, taking into account real project situations. Focusing on the multi-family social housing in the Netherlands, a framework of refurbishment measures that affect the energy efficiency were identified, and their performance was calculated. The energy efficiency indicator is the energy use, together with energy cost reduction and the carbon footprint. Furthermore, the rental price adjustment was estimated, taking into account the refurbishment investment and the exploitation cost of the renovated dwellings. The comparison of the energy use and rental price for the different refurbishment solutions demonstrated the most attractive solutions that the tenants are more likely to accept, taking into account the overall cost of living and sustainability benefits. The results aim at supporting the decision-making discussion between the stakeholders, primarily housing associations and tenants.

2. Methodology

To provide insights to the study's question on the relation between energy-efficiency renovation and cost of living, the evaluation of the refurbishment options is based on Key Performance Indicators (KPIs), as they were concluded from focus groups with residents and housing associations. The KPIs that are considered important for the different groups are the energy use and its resulting cost, the sustainability of the solutions, expressed by the greenhouse gases (GHG) emissions, the rent price because it reflects the refurbishment costs (section 2.4), and the resulting total cost of living. Those factors are considered as an important motivation for energy efficiency measures, as they are of personal relevance for the users, who are the end target of the study's information. The extent to which something is personally relevant to an individual depends on self-concepts, values, needs and goals. (Baumhof et al., 2018)

Table 1. Overview of KPIs

KPI	Unit	Calculation method
Energy use	kWh/m2 per yr	Dynamic simulation, as described in 2.3
GHG emissions	kgCO2eq./yr	Based on the energy consumption, according to the factors of Table 3
Energy cost	€/month	Based on the energy consumption, according to the prices of Table 3
Rent	€/month	Calculated by taking into account the renovation investment, as explained in 2.4
Total cost of living	€/month	The sum of energy cost and rent (as shown in Figure 4)

To quantify those KPIs, the refurbishment measures were systematically organised and their effect on energy use, cost and rental price was calculated. The investigation is based on refurbishment strategies for two case-study buildings, which represent typical tenement apartment buildings in the Netherlands. The specifics of each building were taken into account for not only the measures

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applied but also in the design option and assumptions considered for the energy and cost calculations.

The steps of the study's methodology, thus, begin with the selection of the appropriate case-study buildings and the definition of the type and variations of the interventions, compiling a transformation framework. Based on this framework, renovation strategies are composed as combinations of the parameters variation, and they are then calculated in terms of energy performance and cost. Those steps are explained in more detail in the respective sections below.

2.1. Case-study buildings

The study focuses on low-rise, multi-family, walk-up (or tenement) apartments, as they present considerable challenges for their energy upgrade. In 2016, there are still 799,956 apartments of all types from the period 1906-1965 left in The Netherlands. That's about 10.47% of the current Dutch housing stock. In Amsterdam there are still 155,456 apartments (36,6%), in Rotterdam 104,014 (33,4%), in Den Haag 107,253 (42,4%), and in Utrecht 29,482 (19,7%) (CBS, 2017), which adds up to about 400,000 apartments in the four cities.

Within the particular building type, buildings from different periods are included, presenting similarities and differences with each other. Differences include the construction method or the building layout in the plot. On the other hand, about 80% of the apartments have more or less the same size and spatial arrangement with two or three bedrooms and an average of 50-70 square meters of useful floor area (Priemus and Elk, 1971). Moreover, the challenges to upgrade the walk-up apartments are similar for the building types. Those challenges are related with the necessity for renovation in an inhabited state, as well as the stagnation of tenant mobility as the buildings were not equipped with ramps and elevators at the time of construction (Oorschot L et al., 2018). Most importantly, the energy performance of those building is low and needs to improve, in order to reach the goal for carbon neutral building stock by 2050.

To address the differences encountered in the building stock, the study considered two tenement apartment building, one from the post-war period (Figure 1) and one from the inter-war period (Figure 2). Those buildings were identified by the housing associations as relevant, firstly, as representative of their type, and secondly as being part of their renovation plans in the near future. The specific programme and requirements, also provided by the housing associations managing the buildings, were used to define the options and the combinations applied in each case.

Figure 1. Design Case 1 (DC1): Post-war period Camera Obscura, Overvecht Utrecht, 2016

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Figure 2. Design Case 2 (DC2): Interwar period. Surinaamseplein, Amsterdam.

2.2. Define the alternatives and the combinations

To be able to evaluate the solution, the alternative refurbishment measures need to be defined. The measures are defined per category and per function, creating a "General Transformation Framework". The parameters taken into account for the framework development came out of research the existing tenement building types of the inter-war and post-war period and their special characteristics and projects (Oorschot L et al., 2018). Moreover, analysis of realised refurbishment project and interviews with architects and housing association helped to define the state-of-the-art. In the scope of the present study, the measures discussed refer to a cluster of technical interventions that can be employed to improve the energy efficiency of the apartments. Additional socio-cultural interventions related to the functional and cultural heritage qualities are possible to be applied, but outside the present paper's scope.

Nevertheless, as likely they are not applied individually, the measures have been combined into integrated strategies. The aspects applied in each case are not always the same, as they needed to comply with the specifics of the given building, in terms of feasibility, but also project objectives.

2.3. Energy demand calculation and indicators

The energy use for both building and user-related sources is calculated by means of dynamic thermal performance simulation. Then the energy use is simulated after the proposed, combined solutions have been applied. The software used for the thermal simulation is DesignBuilder, as appropriate for the purpose of this study, because it can generate a range of environmental performance data such as energy consumption and internal comfort data. It provides a modelling interface, integrated with EnergyPlus, which is the U.S. DOE building energy simulation program for modelling building heating, cooling, lighting, ventilating and other energy flows. The output is based on detailed sub-hourly simulation time steps using the EnergyPlus simulation engine(DOE, 2012), classified as "Tailored

doi:10.1108/SASBE-04-2019-0044

rating", according to European Standards EN15603 (2008). The software calculates heating and cooling loads using the ASHRAE-approved "Heat Balance" method implemented in EnergyPlus (DesignBuilder, 2012). The actual data for the building's size and construction were used, data for the location climate were input, and occupancy data were based on the building's function. The different inputs are summarised in Table 2.

For every energy consumption calculation, the way the building is constructed and operated needs to be specified, as inputs. When comparing current and new energy demand, an assumption is that the usage patterns will not change significantly. Typical is the type of apartment that is repeated more times and its energy savings are then more important for the total savings of the block. In apartment buildings, typical in most cases is a middle apartment, in a middle floor (Figure 3).

Table 2 Energy simulation inputs

Parameter	Inputs
Location	Netherlands
Orientation	Depending on specific building
Geometry and zones	Every room as a different zone, depending on activity (bedroom, living room, etc.)
Schedules and occupancy	Based on zones' function, for a four-person household (family with two parents and two children)
Apartment type	Middle apartment
BUILDING ELEMENTS AND THERMAL PROPERTIES	Existing building Refurbished: According to thermal envelope options
Openings	Layout: per building and design. Window wall ration between 60-30%
Heating	Existing building: Gas boiler, efficiency 80% Refurbished: According to options
Ventilation	Existing building: Natural ventilation Refurbished: According to options
DHW	9,6 l/m2/day, for a four-person household and the 20m2 of the wet spaces in the dwelling. Based on average per day is 120l, 40% warm (WMDwater, 2016)
Energy generation	Calculated per apartment, based on the overall available area for PV application. Efficiency 255Wp

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Figure 3. Design Builder model visualisation DC1 and DC2. The middle apartment is the reference.

The simulation resulted in the amount of energy in kWh a dwelling requires per year, including HVAC systems, domestic hot water and appliances. Moreover, the internal temperatures were checked to calibrate the dwelling function and comfort, existing and refurbished, and ensure that overheating is avoided.

The energy costs are based on the prices indicated in Table 3, considering fixed amounts for the grid, the tax, as well as different prices for peak hours. Those prices are then implemented to the simulation results for the energy demand by the respective energy sources, which will be explained in section 3, namely gas, electricity, pellets and district heating. The savings in CO2eq. are calculated to the original situation. The CO2eq. produced in every case is calculated based on the simulated energy demand in kWh. However the different fuels that are used in every model have different conversion factors kWh to kgCO2eq., according to CO2-emissiefactoren (2017)

Table 3 Energy cost and CO2eq. emission factors for different sources

	€ /unit consumption	**Fixed costs**	**kgCO2eq. /unit consumption**
Gas	$0{,}42/m^3+0{,}32\ /m^3=0{,}74/m^3$ (1)	236,69€	1,89/m3 (4)
Electricity	0,078/kWh+0,12/kWh =0,15 (1)		0,4133/kWh (4)
Pellet	0,06358 € /kWh 0,295 € /kg (2)	N/A	0,089/kWh (5)
District heating	22,27 € /GJ 0,08 € /kWh (3)	465€	0,12959/kWh (6)

(1) https://www.eneco.nl/
(2) 1000kg houtpellets cost 295 euro, inclus. 21% BTW. Regarding the efficiency, we assume 16,7 MJ/kg. http://www.houtpellets-online.eu/winkel/
(3) https://www.nuon.nl/media/service/downloads/warmte-tarieven-overig/uitleg-tarieven-stadswarmte-kleinverbruik-2017.pdf
(4) https://co2emissiefactoren.nl/lijst-emissiefactoren/
(5) 25,82 kgCO2e/GJ https://co2emissiefactoren.nl/lijst-emissiefactoren/ 25 gCO_2e/MJ http://www.forever-fuels.com/carbon-footprint-wood-pellets (for EU produced pellets)

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(6) Based on 36kgCO2e/GJ (https://co2emissiefactoren.nl/lijst-emissiefactoren/)

2.4. Total cost of living calculation method

The combined refurbishment strategies are evaluated in terms of the effect the investment has on the rent price. To this end, a Life Cycle Costing (LCC) was performed. The method followed is described in the following steps and visualised in Figure 4. The increase in the rent price was based on the assumption that for the operation to be financially sustainable, the housing association must be cover the renovation investment by the apartment exploitation, taking into account a 30-year period.

1. The investment costs of major renovations were determined without energy-saving measures. In this study the investment costs have been defined according to the Dutch standard NEN 2699 (NEN, 2017) and consistent with Dutch building practice, as follows: the value in use of the existing building + the construction costs of the renovation + the additional costs such as fees, connection costs and municipal levies + VAT.
   The construction costs of all renovation measures have been estimated on the basis of EcoQuaestor (2014) cost database. .
2. The investment costs of specific energy-efficiency measures were determined. The effect of those measures on the energy use of the dwellings was determined, as described in the section 2.3.
3. The rent for the apartments after step 1has been determined in accordance with the "Appropriate allocation" scheme under the 2015 Housing Act.
4. The investment (from step 1) is then included in a cash flow survey of operating costs and benefits in accordance with the LCC model of the NEN 2699 standard. In this survey, maintenance, management costs and other property expenses are included in the form of a fixed amount per property at a for the sector typical cost level.
   On the revenue side of the balance sheet, the present value of 30 years of rental income (from step 3) has been set, assuming that 30 years is the exploitation period for an apartment in the social housing sector.
5. The extra investment costs of the specific measures (from step 2) were included in the cash flow survey (from step 4). And (the present value of) the rental income was adjusted in order to close the balance again.
6. The increase in the monthly rent was then determined on the basis of the figures from step 5.
7. The estimated average amount of energy costs is added to the rent (from step 3).

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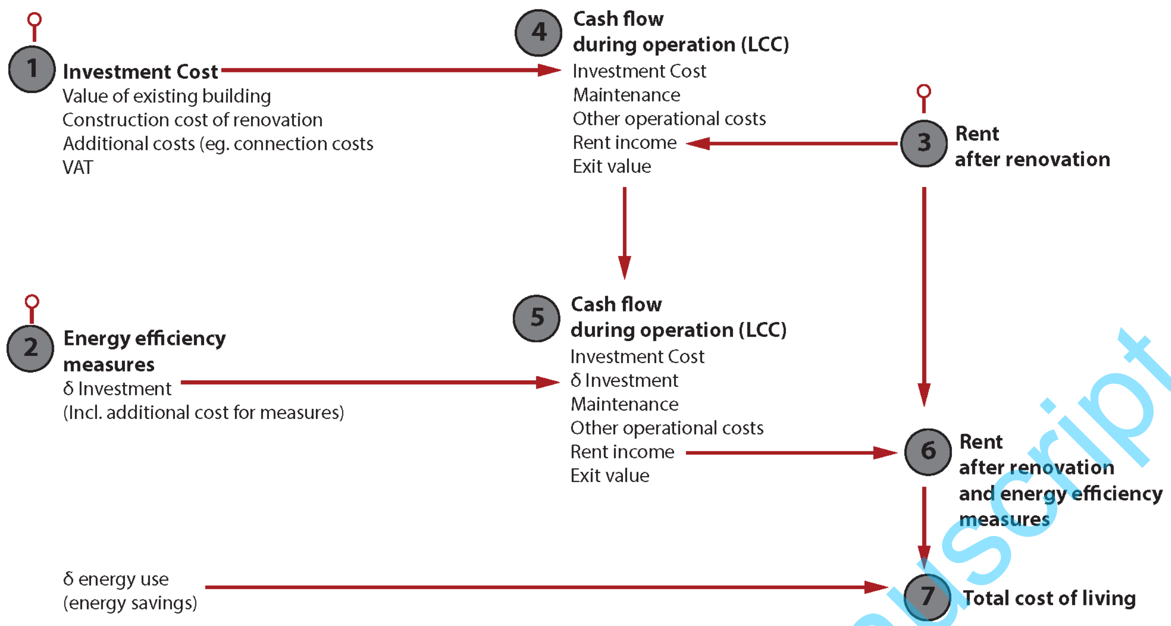

Figure 4. Establishing the relation between investment costs and housing expenses

It needs to be clarified that this method can result in differences in the rent price for the same combinations of energy efficiency measures combinations. The reason for this discrepancy is the defined rent after renovation in step (3), which also depends in other parameters, such as additional rooms, or the construction of extra dwellings, which are not within the scope of the current study, which aims at verifing whether the savings on energy costs are greater (or at least not smaller) than the capital burden of the energy-saving measures.

3. General Transformation Framework: alternative refurbishment measures

The alternative measures were defined based on analysis of current refurbishment practice, literature review and discussions with stakeholders. The transformation options, organised per aspect, create a framework. The aspects considered that have an impact on the energy use of the building are the following:

1. Façade Design

The design of the façade, openings and operation, influences the energy loses through the façade and, hence, the energy needed to heat the building. Moreover, the lighting energy use depends on the transparency and the window-to-wall ratio (WWR). The three designs are investigated in DC1, that differ in the design of the windows and the ventilation openings, preserving, nevertheless the characteristics of the original façade design.

2. Extension

An option encountered in renovation projects is the construction of wintergarden (Konstantinou and Dimitrijević, 2018), either by cladding the existing balconies or by new constructionThe main benefit of such a measure is the extension of the living space with comfort temperatures for a large while at the same time, it acts as a buffer zone, resulting in lower heat losses.For the present study, the option considered included an additional construction, with mostly glazed external wall, having as a reference the project Tour Bois-le-Prêtre by Druot, Lacaton & Vassal. The new living space is not

doi:10.1108/SASBE-04-2019-0044

conditioned. Hence, the interior partition, previously external wall, featured insulated windows. Both interior and exterior windows are operable

3. Thermal properties upgrade

Updating thermal resistance and airtightness of the building envelope if the first step to improve the energy performance of the building, by reducing the heat losses. The level of thermal resistance depends on the components specifications, such as the type and thickness of insulation materials and the type of glazing. For the study, two levels of thermal envelope are considered; Both have a U-value coefficient of 0.20 W/m2K for the opaque elements. The glazing type differs, from double glazing for the basic level to triple glazing for the high-level intervention.

4. Heating system

The efficiency and the energy source of the heating system determine final and the primary energy consumption. Three commonly used systems that were evaluated in DC2, to be considered in the buildings' upgrades; air-to-water heat pump, pellet boiler and district heating network at high temperature.

5. Ventilation system

Three different ventilation strategies were tested for their effect on the energy demand; natural inlet-mechanical outlet, mechanical inlet and outlet with heat recovery and decentral units with heat recovery in the living room.

6. Renewable energy

Energy generation is a necessary step in the ambition to achieve energy neutrality on building level, and it is also a common consideration in energy efficiency upgrades. Photovoltaic panels that produce electricity and solar panels for DHW are the options in the transformation framework of this study.

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doi:10.1108/SASBE-04-2019-0044

Figure 5 Overview of the alternative refurbishment solutions proposed (based onOorschot L et al., 2018)

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4. Overview of the results

The simulation of the energy performance of the renovated building provided data on final energy demand, its respective cost, and the related CO2eq. emissions, for the different refurbishment strategies. The comparison of this information allowed to identify the most and least efficient combinations, but also the effectiveness of the different aspects.

Table 4 and Table 5 present the overview of the renovation strategies that were calculated to have the minimum and maximum value for the different KPI's. As explained before, different aspects were tested in each case, with the goal apply strategies that were relevant for the case-specific. For example, in DC1, the heating system applied was always a gas-fuelled hydronic system with an efficiency of 90%, as it was not in the scope of the specific case-study to modify the heating source. On the other hand, in DC2, the thermal envelop upgrade was in always the more advanced level (A+), since a high energy performance was in the renovation objectives. As a result, each of the two cases provides insights on different aspects. In this way, the results are more comparable, because we minimise the parameters that vary due to different building context, such as the apartment size, the rent, or different renovation initial investment. To highlight the focus, only the aspects that do vary per case are included in the respective tables.

More specifically in the Table 4 and Table 5 and in section 5, DC1 is considered regarding the façade design, the extension construction, the upgrade of the thermal propreties and the renewable energy sources (RES). Different systems for heating and ventilation were applied in DC2.

Looking at the combination of renovation measures in DC1, a pattern in the options providing either minimum and maximum value for the KPI's can be found. The GHG emissions are excluded because the same fuel and system are applied in all combinations. Thus, the minimum and maximum combination are the same as for the energy use, since the same factor for CO2eq. applies.

The moderate thermal envelope upgrade (B), combined with the installation of both PV and solar collectors and without the construction of the wintergarden has the lowest costs. Moreover, it can be observed that the higher upgrade of the thermal envelope results is higher rent cost, but lower energy cost and use, as expected.

Table 4 Overview of max, min and average performance for the combinations of DC1

		Aspects								
		Façade Design	**Thermal envelope**	**Extension**	**RES**	**Energy use (kWh/m2)**	**Energy cost €/month**	**GHG (kgCO2 eq./yr)**	**Total cost of living (€/ month)**	**Rent price €/mnd**
DC1		Current	Current	No extension	None	197	121	3191	711	590
Total cost of Living	MIN	Existing	B	No extension	PV+solar	45	50	1004	653	603
	MAX	Open	A+	Serre	None	75	78	1880	734	657

doi:10.1108/SASBE-04-2019-0044

Rent	MIN	HalfOpen	B	No extension	Gas	84	73	1738	665	592
	MAX	Open	A+	Serre	PV+solar	42	54	1133	723	669
Energy Cost	MIN	Existing	A+	No extension	PV+solar	39	**48**	931	651	603
		Open	A+	No extension	PV+solar	39	**48**	930	653	605
	MAX	Open	B	Serre	None	77	**78**	1901	672	594
		Open	B	Serre	None	77	**78**	1901	669	590
Energy use	MIN	Open	A+	No extension	PV+solar	**39**	48	930	653	605
	MAX	Existing	B	Serre	None	**77**	78	1901	669	590

Regarding DC2, the calculation showed that combinations of the suggested options can result in cost of living higher than the current. This increase can be explained by the fact that there is always an increase in the rent and in some combinations the increase is considerable, as a result of the measures costs. It is worth highlighting that in DC2 the thermal envelope is always upgraded to the more advanced level. On the other hand, the energy cost is decreased, but not always enough to compensate for the rent increase. It can also be observed that there is a discrepancy between the maximum and minimum energy cost and the energy use combinations, in the sense that the energy source with the higher energy use offers the lower energy cost. This can be attributed to the different pricing schemes of each energy source.

Table 5 Overview of max, min and average performance for the combinations of DC2

		Aspects							
		Heating	**Ventilation**	**RES**	**Energy use (kWh/ m2)**	**Energy cost €/month**	**kgCO2 eq./yr**	**Total cost of living/ month**	**Rent price €/mnd**
		Gas	Nat/mech	None	187	125	3307	715	590
Total cost of Living	MIN	Pellet	Nat/mech	PV	68	52	1041	**653**	601
	MAX	District	Decentral	PV	62	91	1019	**837**	746
Rent	MIN	Pellet	Nat/mech	None	82	63	1403	658	**596**
		District	Nat/mech	None	78	103	1477	699	**596**
		Pellet	Decentral	None	84	63	1417	659	**596**
		District	Decentral	None	81	104	1497	700	**596**

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	MAX	Pellet	Nat/mech	PV	63	48	929	794	**746**
		Pellet	Decentral	PV	65	49	942	795	**746**
		District	HeatRecov	PV	55	87	955	833	**746**
		Heatpump	Decentral	PV	52	63	1431	809	**746**
Energy Cost	MIN	Pellet	HeatRecov	PV	59	**47**	906	793	746
	MAX	District	Decentral	None	81	**104**	1497	700	596
Energy use	MIN	Heatpump	HeatRecov	PV	**50**	61	1384	749	688
	MAX	Pellet	Decentral	None	**84**	63	1417	659	596

5. Comparison of the different aspects' variations

This section presents the effect of each aspect, as defined in Figure 5, on the KPI's energy cost, , rent price, total cost of living, energy use and CO2eq. emissions. The costs are monthly per apartment. The sustainability of the solutions is indicated by the energy demand in kWh/m2 yearly as in most of the discussed combination the energy demand and CO2eq. emissions are proportional. When the energy source is relevant and differs per solution, particularly in the case of heating system, the CO2 eq emissions, in kgCO2eq. are also discussed.

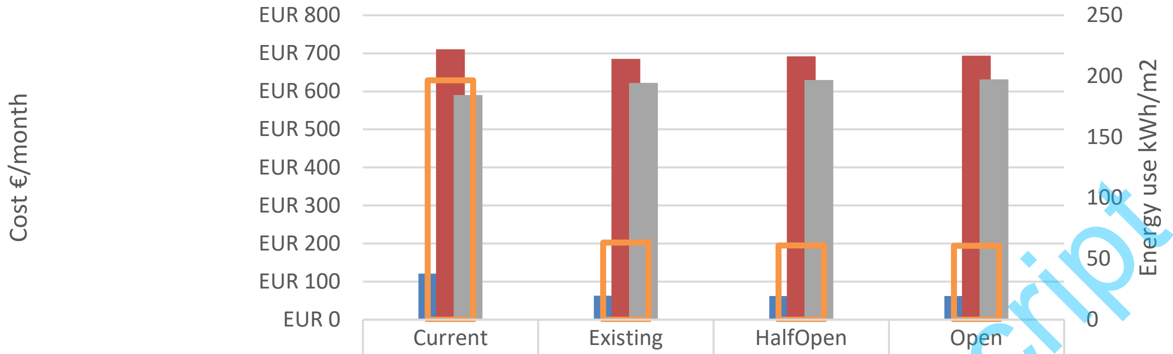
5.1. Façade Design

There were three different options for the façade design. Those options differ in the window-to-wall ratio (WWR), layout and operation. The design of the façade is important for how the building is perceived, and our proposals came out of the analysis of the building characteristics and discussions with architects and housing associations.

Comparing the performance of the three façade designs, however, we can see that energy demand and, hence the energy cost, does not differ significantly, as shown in Figure 6. This similarity can be explained by the thermal properties of the different options, which are all upgraded to high thermal resistance. It is also the reason why there is a 50% reduction in the energy costs and 68% reduction in the energy demand, compared with the current building. Moreover, the WWR is all three variations are relatively high, ranging between 60% and 100%. Therefore the heat losses from the glazing, as well as solar heat gains are similar, resulting in similar energy use in the refurbished apartments. The choice of high WWR is consistent with heritage values of the existing building design.

doi:10.1108/SASBE-04-2019-0044

Finally, the investment for the new façade, and the resulting rent increase is also similar, with the option of preserving the existing façade layout being marginally more economical. Nevertheless, the total cost of living is lower by 7%.

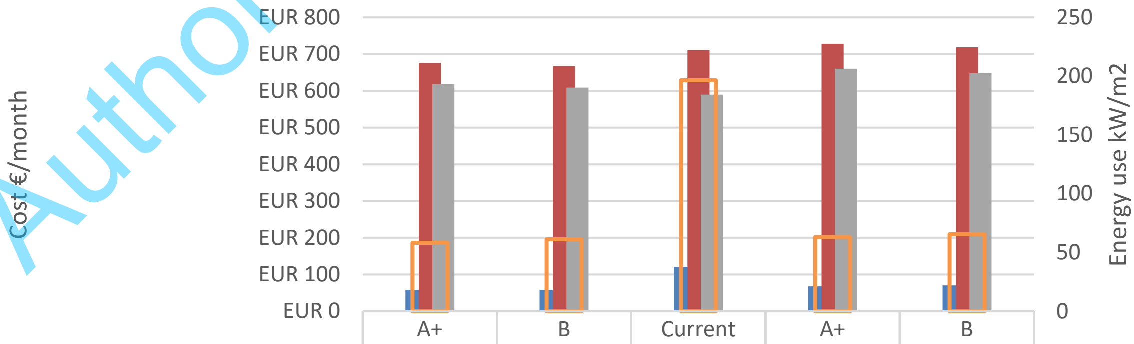


	Current	Existing	HalfOpen	Open
Average of Energy cost €/month	121	63	62	62
Average of Total cost of living €/month	711	686	692	693
Average of Rent €/month	590	623	630	631
Average of Energy use kWh/m2	197	63	61	61

Figure 6 Comparison of the Façade design variations and the current building, in terms of energy cost, rent, the total cost of living and energy use

5.2. Extension

The option to extend the living space is beneficial for improving the living conditions and functionality of the dwellings, along with benefits for energy use, as explained in section 3. Figure 7 presents an overview of the KPI's with and without the extension construction, in relation with the thermal envelope upgrade. One of the first conclusions is that this investment does affect the rent increase The energy use is higher in the dwellings with the winter garden. The higher energy use can be explained by the additional living spaces, which are not conditioned. The total cost of living is lower than the current when there is no wintergarden and marginally higher (€7-17) in the apartments with the wintergarden. However, in those cases the apartments have additional living spaces.



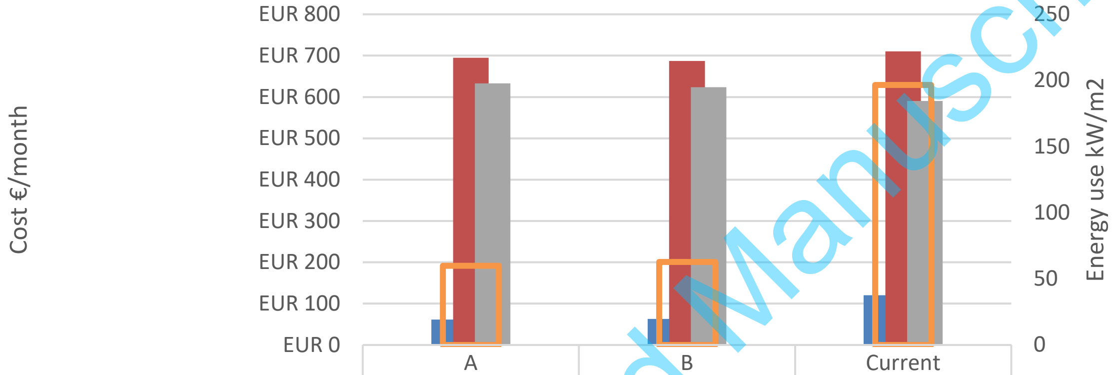
	No extension			Wintergarden	
	A+	B	Current	A+	B
Average of Energy cost €/month	58	59	121	68	70
Average of Total cost of living €/month	676	668	711	728	718
Average of Rent €/month	618	609	590	661	648
Average of Energy use kWh/m2	58	61	197	63	66

doi:10.1108/SASBE-04-2019-0044

Figure 7 Comparison of the winter garden extension in relation to the thermal properties upgrades, in terms of energy cost, rent, the total cost of living and energy use.

5.3. Thermal properties upgrade

The building envelope is upgraded with the application of insulation on the façade and roof, as well as replacement of the windows. The basic upgrade (B) is the minimum required by the regulations in the Netherlands, while the second option (A) is going towards zero energy standards. As can be seen in Figure 7, the difference in the energy demand between the two variations is 5%, which is marginal. The marginal difference can be interpreted by the already good thermal performance of the basic upgrade.. In this sense, the cost-effectiveness of the basic upgrade is better. It needs to be noted, that in both cases the saving to the current energy use is significant and that both options result in lower total cost of living.



	A	B	Current
Average of Energy cost €/month	61	63	121
Average of Total cost of living €/month	695	687	711
Average of Rent €/month	633	624	590
Average of Energy use kWh/m2	60	63	197

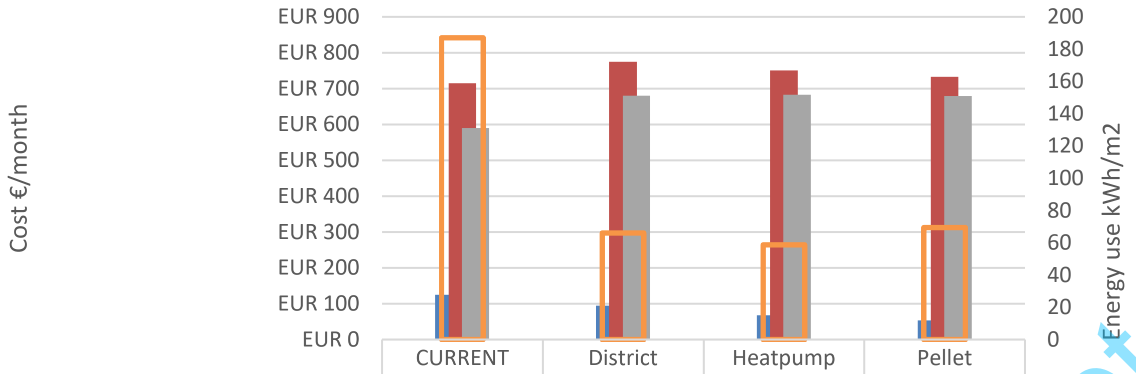
Figure 8 Comparison of the thermal properties upgrade options and the current building, in terms of energy cost, rent, the total cost of living and energy use

5.4. Heating

In the case of the different heating systems, one first observation is that all options lead on average to considerably higher mothly rent, resulting to a higher cost of leaving. There are some combination, as presented in Table 5, which result to lower cost of living, but on average the cost of living is increased. In DC2 the thermal envelope upgrade is always at an advanced level, which can explain the high investment resulting in higher rent. The good envelope performance is also reflected to the significant reduction in energy use, for all heating system options. However, the decrease in energy use is not proportional to the reduction in energy costs and total cost of living (Figure 9) nor the CO2eq. emmissions (Figure 10).

More specifically, the heatpump, despite the lower energy use in kWh which can be attributed to the high COP, results in higher rent than all three options, due to the initial costs. The option of district heating has the highest energy costs resulting in the highest total cost of living, because the monthly fee for district heating includes significant fixed connection costs (Table 3). The pellets as a fuel is cheaper, which is reflected in the lowest energy cost.

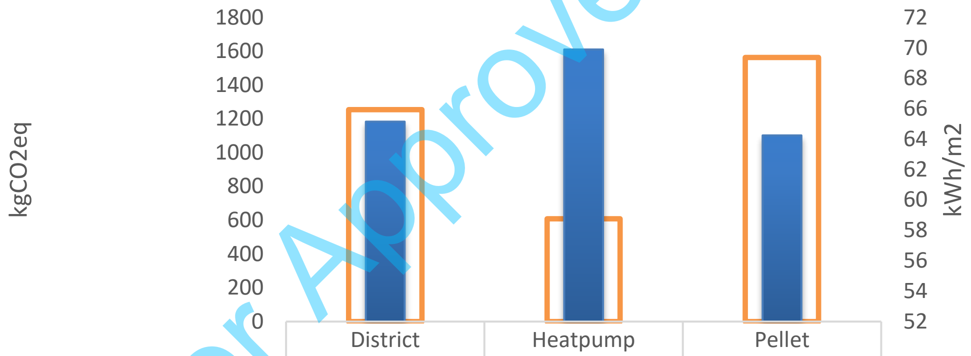
doi:10.1108/SASBE-04-2019-0044



	CURRENT	District	Heatpump	Pellet
Average of Energy cost €/month	125	95	68	53
Average of Total cost of living €/month	715	775	751	732
Average of Rent €/month	590	680	683	679
Average of Energie use (kWh/m2)	187	66	59	69

Figure 9 Comparison of the heating systems options and the current building, in terms of energy cost, rent, the total cost of living and energy use.

Regarding the CO2eq. emmissions, the option of a pellet boiler proves to emmit less CO2eq., despite the higher energy use. This can be explained by the low Primary Energy factor (Table 3) than the electricity of the heatpump.



	District	Heatpump	Pellet
Average of Energie use (kWh/m2)	66	59	69
Average of kgCO2 eq./yr	1184	1612	1103

Figure 10 Energy use in kWh/m2 per year and GHG in kgCO2eq./yr per dwelling, for the respective heating systems options

5.5. Ventilation

The results in Figure 11 show that all ventilaiton strategies, since they are combined with the thermal upgrade of the envelope, reduce significanly the energy use. Comparing them with each other, the ventilation with hear recover reduces the energy use the most, but its cost is reflected in the increase in the rent and the total cost of living. The decentral ventilation strategy results on average in lower cost of living than the other ventilation strategies.

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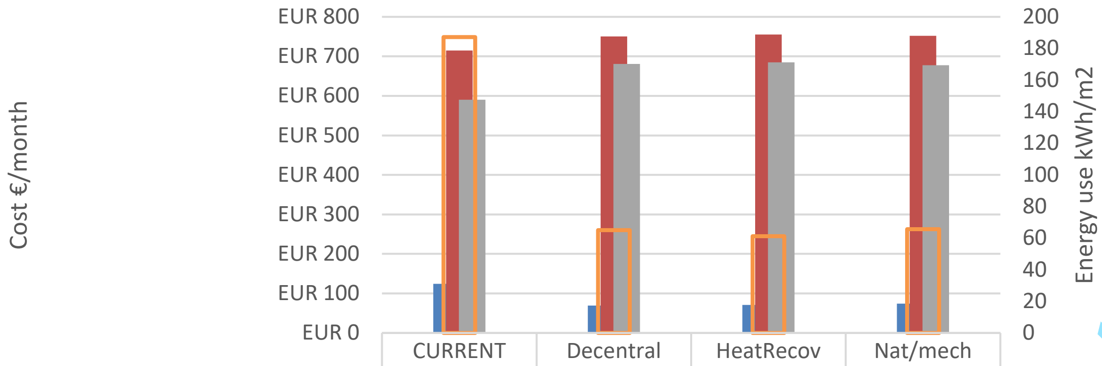
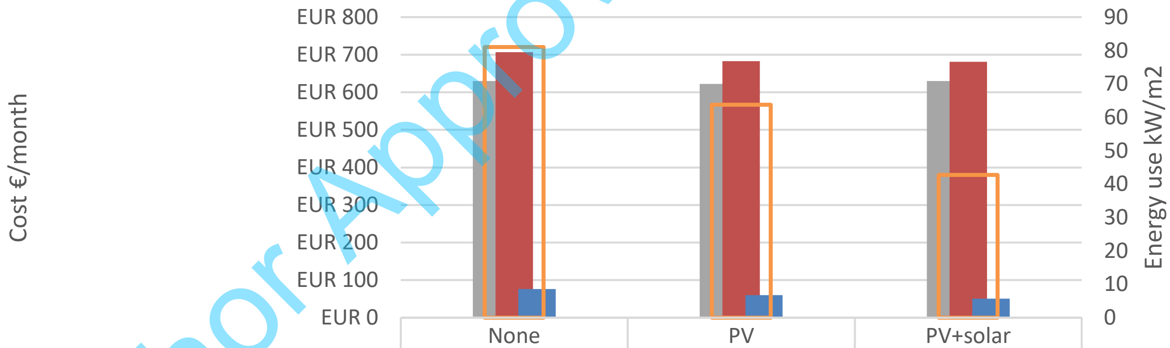


	CURRENT	Decentral	HeatRecov	Nat/mech
Average of Energy cost €/month	125	70	71	74
Average of Total cost of living €/month	715	750	755	752
Average of Rent €/month	590	681	685	677
Average of Energie use (kWh/m2)	187	65	61	66

Figure 11 Comparison of the ventilation system options and the current building, in terms of energy cost, rent, the total cost of living and GHG.

5.6. Renewable

As shown in the results in Figure 5, the application of renewable energy production technology can cut almost in half the energy use and 1/3 the energy cost. The rent, on the other hand, is not affected by the initial investment. The combination of PV panels and solar panels, which applied in DC1 covered the DHW demand, is the most effective option.



	None	PV	PV+solar
Average of Rent €/month	630	622	630
Average of Total cost of living €/month	706	682	681
Average of Energy cost €/month	77	60	51
Average of Energy use kWh/m2	81	64	43

Figure 12 Overview of the renewable energy option applied in DC1, in terms of energy cost, rent, the total cost of living and energy use.

6. Conclusions

The current paper described a methodology to combine the cost and the savings of energy efficiency upgrades in dwellings' refurbishment and identify the effect of design variation. Based on the aspects evaluated, the following main conclusions can be drawn.

doi:10.1108/SASBE-04-2019-0044

1. All tested combination of variables resulted in significant energy savings, up to 70%, due to the proposed the thermal envelope upgrade
2. The variations in the façade design, given similar thermal properties, have a marginal effect on the energy demand
3. The construction of a winter garden is possible without significant increase in the total cost of living
4. Heating systems play a big role in the sustainability of the solution. However it also inflluences the cost of living. Out of the three options tested, the pellet boiler if the most cost-effective, despite not being the most energy efficient.
5. The ventilation system has a direct effect on energy reduction. On average all three option result in comparable total cost of living.
6. Energy generation through the use of PV and solar collectors is cost-effective, as it has a considerable positive effect on the energy use and the energy cost, without increasing the rental price.

The approach of the study goes beyond cost-optimality of measures and investigated the relation between energy upgrades and cost, as a way to evaluate design variation and address the lack of information barrier in renovations. Moreover, It also proves that deep renovation is feasible without increase in the total cost of living, which is an important argument to promote renovations.

The importance of the study is that gives a holistic standpoint to the issue of energy upgrades, by quantifying the effect of the potential measures for the whole expolitation period. The cost as a key -if not the most decisive- factor is put into percepective in relation to the benefit, in order to give a direction to the renovation design and arguments for the stakeholders' dialogue. The results of the study can be used to discuss the users' preferences in the renovation options.

One of the main objectives of the study was not only to identify the effect the different parameters would have but also to inform the current practice in the context of energy efficiency upgrades of multi-residential buildings. To this end, the variations studied were selected based on commonly realized upgrades and focus groups with architects and users, which are often guided by other parameters than the energy efficiency alone. As a result, the combinations of measuredo not have the objective of highlighting thedifferences in energy use or cost optimality but to reflect a real-life situation. Thus, even if some of the variations result in non-significant differences for the KPI's, they are still valuable result to support decision making and provide options in the refurbishment strategy design.

The method presented in this paper was based on the energy efficient refurbishment measures and the specific KPI's. Other measures that may not be as cost-effective but do have additional environmental or living quality benefits, which can also increase the property value. These measures cannot be identified with the research method followed, which focused on energy efficiency. Moreover, the study's method looked at the strategy as a whole, using combinations of measures, as they are applied in real situations. The impact of the measures was thus looked at as a part of a strategy and not isolated, which might have highlighted the impact more, but be unlikely to be used in actual projects.

doi:10.1108/SASBE-04-2019-0044

The conclusions on energy efficiency upgrades need to be considered both by the designers and other stakeholders, most importantly the occupants who will benefit of the reduced energy use, but also will need to pay the possible increase in the rent.

Acknowledgements

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