



Delft University of Technology

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

Konstantinou, Thaleia; de Jonge, Tim; Oorschot, Leo; El Messlaki, Sabira; van Oel, Clarine; Asselbergs, Thijs

DOI

[10.1108/SASBE-04-2019-0044](https://doi.org/10.1108/SASBE-04-2019-0044)

Publication date

2020

Document Version

Final published version

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>

Important note

To cite this publication, please use the final published version (if applicable).
Please check the document version above.

Copyright

Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

Takedown policy

Please contact us and provide details if you believe this document breaches copyrights.
We will remove access to the work immediately and investigate your claim.

Green Open Access added to TU Delft Institutional Repository

'You share, we take care!' - Taverne project

<https://www.openaccess.nl/en/you-share-we-take-care>

Otherwise as indicated in the copyright section: the publisher is the copyright holder of this work and the author uses the Dutch legislation to make this work public.

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

Energy
efficiency
upgrades and
cost of living

615

Received 8 April 2019
Revised 24 July 2019
18 September 2019
Accepted 31 October 2019

Thaleia Konstantinou

*Department of Architecture and the Built Environment,
Technische Universiteit Delft, Delft, The Netherlands*

Tim de Jonge

*HU University of Applied Sciences Utrecht,
Utrecht, The Netherlands, and*

Leo Oorschot, Sabira El Messlaki, Clarine van Oel and
Thijs Asselbergs

*Department of Architecture and the Built Environment,
Technische Universiteit Delft, Delft, The Netherlands*

Abstract

Purpose – 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 purpose of this paper is to investigate the relationship between energy efficiency upgrades and the cost of living.

Design/methodology/approach – Focusing on walk-up apartments in the Netherlands, a framework of refurbishment measures that affect the energy efficiency was 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.

Findings – 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. It has shown the potential of the different interventions to improve the performance and living conditions, without necessarily increasing the total cost of living.

Practical implications – Such results aim at supporting the decision making between the stakeholders, primarily housing associations and tenants.

Originality/value – The importance of the study is that it gives a holistic standpoint to the issue of energy upgrades, by quantifying the effect of the potential measures for the whole exploitation period. The cost, as a key, if not the more most decisive, issue, is put into perspective in relation to the benefit, in order to give a direction to the renovation design and arguments for the stakeholders' dialogue. The approach of the study goes beyond cost-optimality of measures and investigated the relation between energy upgrades and cost, as a



Smart and Sustainable Built
Environment
Vol. 9 No. 4, 2020
pp. 615-633

© Emerald Publishing Limited
2046-6099

DOI 10.1108/SASBE-04-2019-0044

This research was funded by Nederlandse Organisatie voor Wetenschappelijk Onderzoek, Research through Design, with Project No. 14569.

way to evaluate design variation and address the lack of information barrier in renovations. Moreover, it also proves that deep renovation is feasible without increasing in the total cost of living, which is a principal argument to promote renovations.

Keywords Renovation, Energy efficiency, Decision making, Residential buildings, Total cost of living, Transformation framework

Paper type Research paper

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, 2011, 2013; 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, 2018) 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 (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/844/EU, 2018).

Moreover, the Dutch housing associations have the ambition to achieve a carbon-neutral building stock by 2050 (AEDES, 2018). 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.*, 2017; 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 per cent 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; Kumbaroglu 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.

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 was 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 I).

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 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 is about 10.47 per cent 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% Industrialisation of building envelope) (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 per cent 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 metres 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 *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 (Plate 1) and one from the

Table I.
Overview of KPIs

| KPI | Unit | Calculation method |
|----------------------|-----------------------------|--|
| Energy use | kWh/m ² per year | Dynamic simulation, as described in 2.3 |
| GHG emissions | kgCO ₂ eq./year | Based on the energy consumption, according to the factors of Table III |
| Energy cost | €/month | Based on the energy consumption, according to the prices of Table III |
| 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) |

Plate 1.
Design Case 1 (DC1):
post-war period



Note: Camera Obscura, Overvecht Utrecht, 2016

inter-war period (Plate 2). Those buildings were identified by the housing associations as relevant, first, as representative of their type, and second 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.

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 *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 US Department of Energy (DOE) building energy simulation programme for modelling building heating, cooling, lighting, ventilating and other energy flows. The output is based on detailed sub-hourly



Note: Surinaamseplein, Amsterdam

Plate 2.
Design Case 2 (DC2):
interwar period

simulation time steps using the EnergyPlus simulation engine, classified as “Tailored 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 II](#).

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 1](#)).

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

Table II.
Energy simulation
inputs

| Parameter | Inputs |
|--|--|
| Location | The 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 and30% |
| Heating | Existing building: gas boiler, efficiency 80% Refurbished: according to options |
| Ventilation | Existing building: natural ventilation Refurbished: according to options |
| DHW | 9.6 L/m ² /day, for a four-person household and the 20 m ² of the wet spaces in the dwelling. Based on average per day is 120 L, 40% warm (WMDwater, 2016) |
| Energy generation | Calculated per apartment, based on the overall available area for PV application. Efficiency 255Wp |

Figure 1.
Design builder model
visualisation DC1
and DC2



Note: The middle apartment is the reference

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 III, 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).

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 2. The increase in the rent price was based on the assumption that for the operation to be financially sustainable,

| | €/unit consumption | Fixed costs | kgCO ₂ eq./unit consumption |
|------------------|--|-------------|--|
| Gas | $0.42/\text{m}^3 + 0.32/\text{m}^3 = 0.74/\text{m}^3$ ^a | 236,69 € | $1.89/\text{m}^3$ ^d |
| Electricity | $0.078/\text{kWh} + 0.12/\text{kWh} = 0.15$ ^a | | $0.4133/\text{kWh}$ ^d |
| Pellet | 0.06358 €/kWh 0.295 €/kg ^b | n/a | $0.089/\text{kWh}$ ^c |
| District heating | 22.27 €/GJ 0.08 €/kWh ^c | 465 € | $0.12959/\text{kWh}$ ^f |

Notes: ^awww.eneco.nl/; ^b1000 kg houtpellets cost 295€, inclus. 21 per cent BTW. Regarding the efficiency, we assume 16,7 MJ/kg.www.houtpellets-online.eu/winkel/; ^cwww.nuon.nl/media/service/downloads/warmte-tarieven-overig/uitleg-tarieven-stadswarmte-kleinverbruik-2017.pdf; ^d<https://co2emissiefactoren.nl/lijt-emissiefactoren/>; ^e25.82 kgCO₂e/GJ <https://co2emissiefactoren.nl/lijt-emissiefactoren/> 25 gCO₂e/MJ www.forever-fuels.com/carbon-footprint-wood-pellets (for EU produced pellets); ^fbased on 36 kgCO₂e/GJ (<https://co2emissiefactoren.nl/lijt-emissiefactoren/>)

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

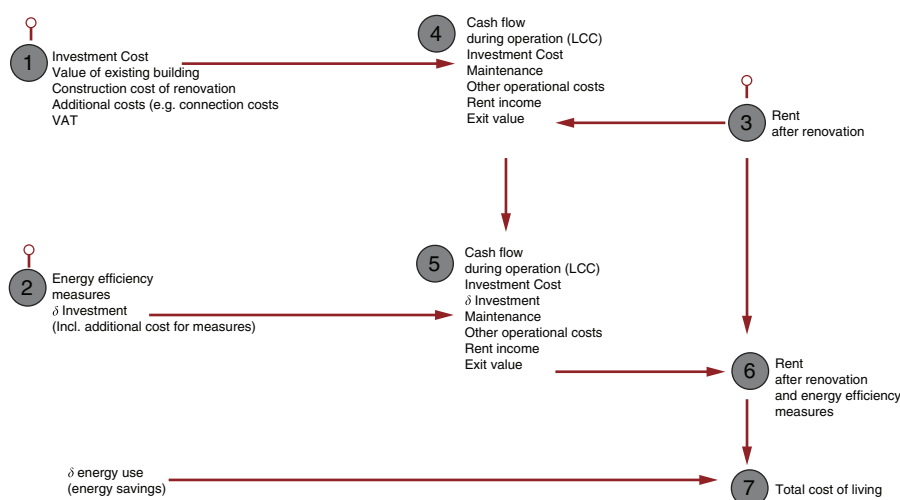


Figure 2.
Establishing the
relation between
investment costs and
housing expenses

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, and
 - 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 1 has 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).

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 verifying 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:

3.1 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.

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

3.3 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 $0.20 \text{ W/m}^2 \text{ K}$ for the opaque elements. The glazing type differs from double glazing for the basic level to triple glazing for the high-level intervention.

3.4 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.

3.5 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.

3.6 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.

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.

Tables IV and V 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

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

| | Aspects | | | | | Energy cost €/month | GHG (kgCO2 eq./year) | Total cost of living (€/month) | Rent price €/mnd |
|-----------------------------|------------------|---------------------|-----------------|----------|-------------------------------------|------------------------|-------------------------|-----------------------------------|---------------------|
| | Façade Design | Thermal envelope | Extension | RES | Energy use (kWh/m ²) | | | | |
| <i>DC1</i> | Current | Current | No extension | None | 197 | 121 | 3,191 | 711 | 590 |
| <i>Total cost of living</i> | | | | | | | | | |
| MIN | Existing | B | No extension | PV+solar | 45 | 50 | 1,004 | 653 | 603 |
| MAX | Open | A+ | Serre | None | 75 | 78 | 1,880 | 734 | 657 |
| <i>Rent</i> | | | | | | | | | |
| MIN | HalfOpen | B | No extension | Gas | 84 | 73 | 1,738 | 665 | 592 |
| MAX | Open | A+ | Serre | PV+solar | 42 | 54 | 1,133 | 723 | 669 |
| <i>Energy cost</i> | | | | | | | | | |
| 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 | 1,901 | 672 | 594 |
| | Open | B | Serre | None | 77 | 78 | 1,901 | 669 | 590 |
| <i>Energy use</i> | | | | | | | | | |
| MIN | Open | A+ | No extension | PV+solar | 39 | 48 | 930 | 653 | 605 |
| MAX | Existing | B | Serre | None | 77 | 78 | 1,901 | 669 | 590 |

| Aspects | | | | Energy use (kWh/m ²) | Energy cost €/month | kgCO2 eq./year | Total cost of living/ month | Rent price €/mnd |
|-----------------------------|-------------|-----------|------|-------------------------------------|------------------------|-------------------|-----------------------------------|---------------------|
| Heating | Ventilation | RES | | | | | | |
| Gas | Nat/mech | None | | 187 | 125 | 3,307 | 715 | 590 |
| <i>Total cost of living</i> | | | | | | | | |
| MIN | Pellet | Nat/mech | PV | 68 | 52 | 1,041 | 653 | 601 |
| MAX | District | Decentral | PV | 62 | 91 | 1,019 | 837 | 746 |
| <i>Rent</i> | | | | | | | | |
| MIN | Pellet | Nat/mech | None | 82 | 63 | 1,403 | 658 | 596 |
| | District | Nat/mech | None | 78 | 103 | 1,477 | 699 | 596 |
| | Pellet | Decentral | None | 84 | 63 | 1,417 | 659 | 596 |
| | District | Decentral | None | 81 | 104 | 1,497 | 700 | 596 |
| 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 | 1,431 | 809 | 746 |
| <i>Energy cost</i> | | | | | | | | |
| MIN | Pellet | HeatRecov | PV | 59 | 47 | 906 | 793 | 746 |
| MAX | District | Decentral | None | 81 | 104 | 1,497 | 700 | 596 |
| <i>Energy use</i> | | | | | | | | |
| MIN | Heatpump | HeatRecov | PV | 50 | 61 | 1,384 | 749 | 688 |
| MAX | Pellet | Decentral | None | 84 | 63 | 1,417 | 659 | 596 |

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

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 [Tables IV and V](#) and in [Section 5](#), DC1 is considered regarding the façade design, the extension construction, the upgrade of the thermal properties and the renewable energy sources. Different systems for heating and ventilation were applied in DC2.

Looking at the combination of renovation measures in DC1 ([Table IV](#)), 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.







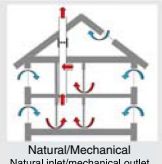


The moderate thermal envelope upgrade (B), combined with the installation of both PV and solar collectors and without the construction of the wintergarden has the lowest costs. Moreover, it can be observed that the higher upgrade of the thermal envelope results in higher rent cost, but lower energy cost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

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.

Figure 3.
Overview of the
alternative
refurbishment
solutions proposed

5. Comparison of the different aspects' variations

This section presents the effect of each aspect, as defined in [Figure 3](#), 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

| GENERAL TRANSFORMATION FRAMEWORK | Intervention A | Intervention B | Intervention C |
|--|--|---|---|
| 01 Façade Design Readability of street façade |  Existing Original facade layout with parapet changes in ground floor |  Half open Floor-to-ceiling windows, ventilation panels on the sides |  Open Floor-to-ceiling sliding doors in concrete frame |
| 02 Extension Construction of wintergarden |  No changes, existing floor plans |  Wintergarden Extension with transparent cladding | |
| 03 Thermal envelope Upgrade thermal resistance of the building envelope | Basic level Energy Performance Certificate B | High level Energy Performance Certificate A++ | |
| 04 Heating system Hydronic system used with radiators |  Heatpump Air-to-water COP 5, Fuel electricity |  Pellet Central building boiler with biomass |  District heating network High temp energy source varies |
| 05 Ventilation system Central/decentral |  Natural/Mechanical Natural inlet/mechanical outlet |  Health recovery Balanced ventilation |  Decentral Ventilation and heating combined |
| 06 Renewable energy On-site production of renewable energy |  No RES |  PV Photovoltaic panels on the roof |  PV+solar Photovoltaic panels and solar collector on the roof/balcony |

Source: Based on Oorschot *et al.* (2018)

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 CO₂eq emissions, in kgCO₂eq. are also discussed.

5.1 Façade design

There were three different options for the façade design. Those options differ in the 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 4. 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 per cent reduction in the energy costs and 68 per cent 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 per cent. 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.

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 per cent.

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 5 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.

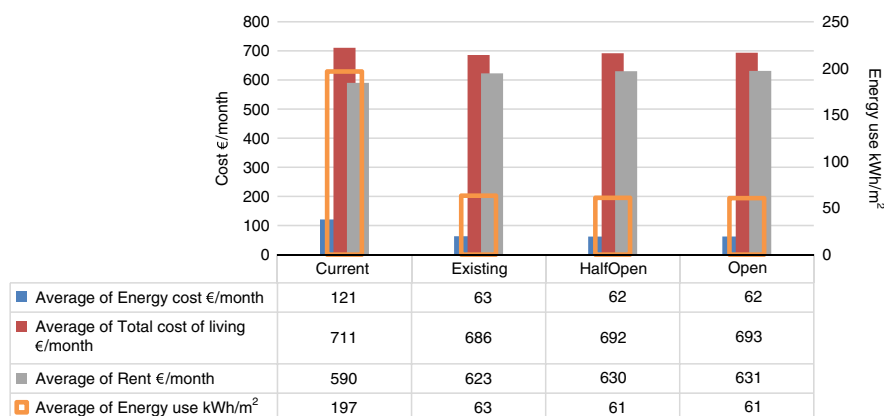


Figure 4. Comparison of the Façade design variations and the current building, in terms of energy cost, rent, the total cost of living and energy use

Figure 5.
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 5, the difference in the energy demand between the two variations is 5 per cent, 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 (Figure 6).

5.4 Heating
In the case of the different heating systems, one first observation is that all options lead on average to considerably higher monthly rent, resulting to a higher cost of living. There are some combination, as presented in Table V, 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

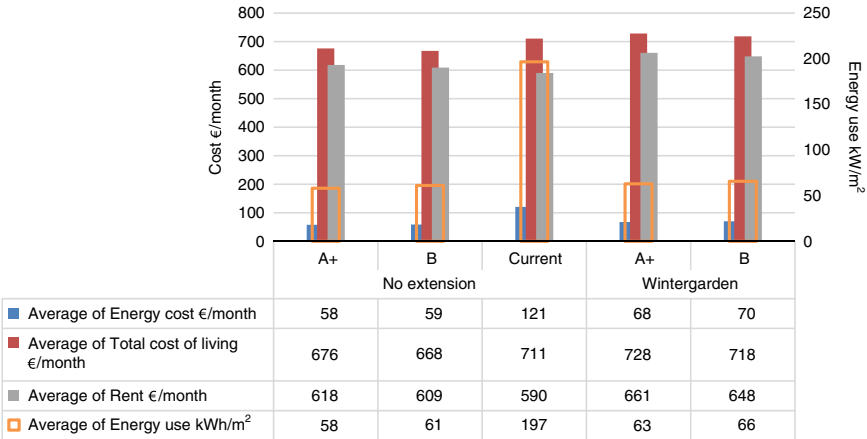
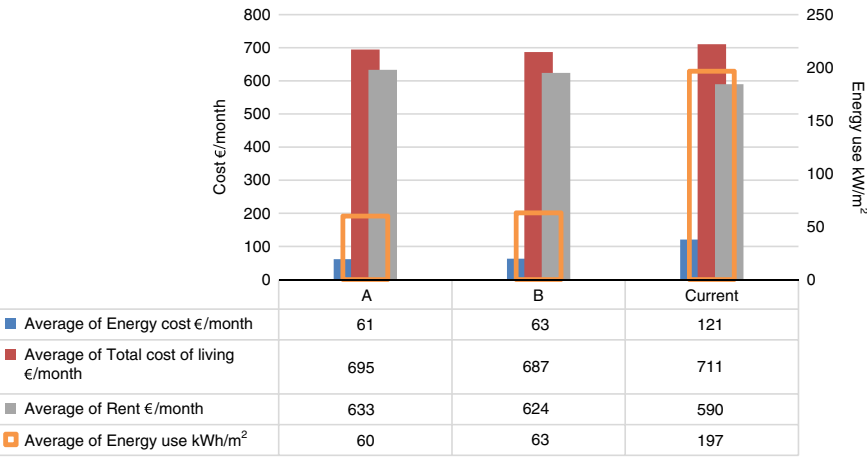


Figure 6.
Comparison of the
thermal properties
upgrade options and
the current building, in
terms of energy cost,
rent, the total cost of
living and energy use



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 7) nor the CO₂eq. emissions (Figure 8).

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 III). The pellets as a fuel is cheaper, which is reflected in the lowest energy cost.

Regarding the CO₂eq. emissions, the option of a pellet boiler proves to emit less CO₂eq., despite the higher energy use. This can be explained by the low Primary Energy factor (Table III) than the electricity of the heat pump.

5.5 Ventilation

The results in Figure 9 show that all ventilation strategies, since they are combined with the thermal upgrade of the envelope, reduce significantly the energy use. Comparing them with each other, the ventilation with hear recover reduces the energy use the most, but its cost is

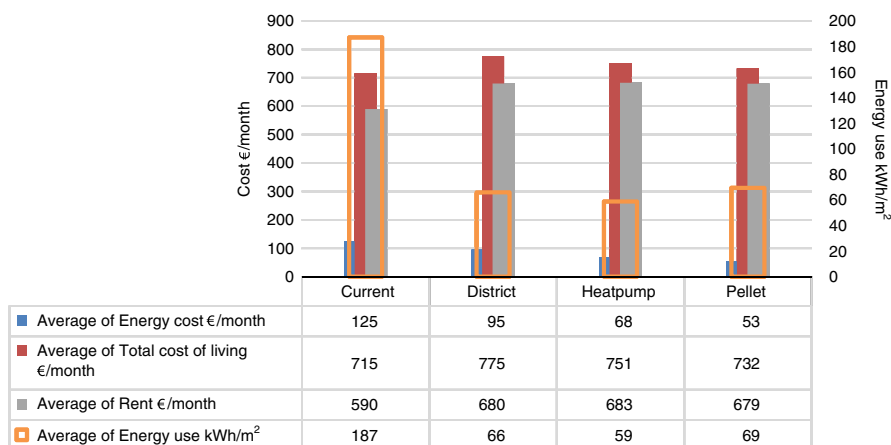


Figure 7.
Comparison of the heating systems options and the current building, in terms of energy cost, rent, the total cost of living and energy use

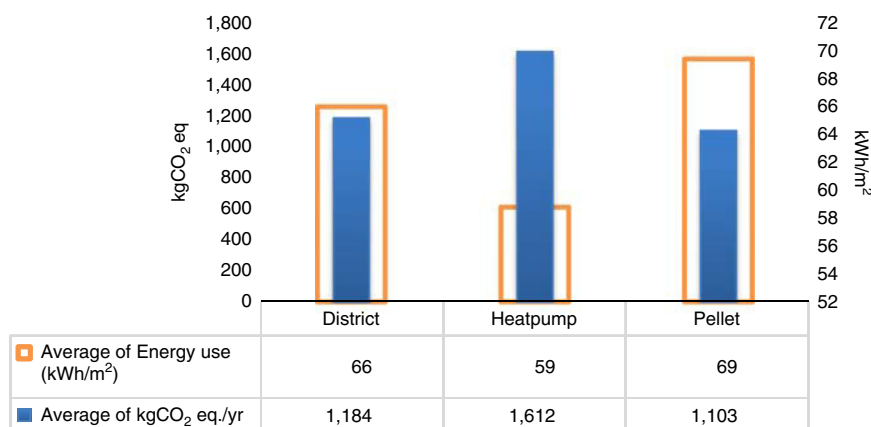


Figure 8.
Energy use in kWh/m² per year and GHG in kgCO₂eq./year per dwelling, for the respective heating systems options

Figure 9.
Comparison of the ventilation system options and the current building, in terms of energy cost, rent, the total cost of living and GHG

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.

5.6 Renewable

As shown in the results in Figure 3, the application of renewable energy production technology can cut almost in half the energy use and one-third 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 (Figure 10).

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:

- (1) All tested combination of variables resulted in significant energy savings, up to 70 per cent, due to the proposed the thermal envelope upgrade.

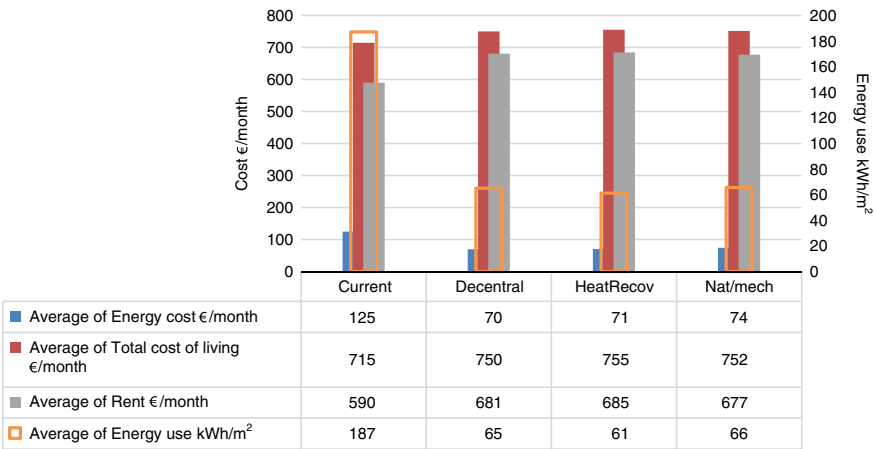
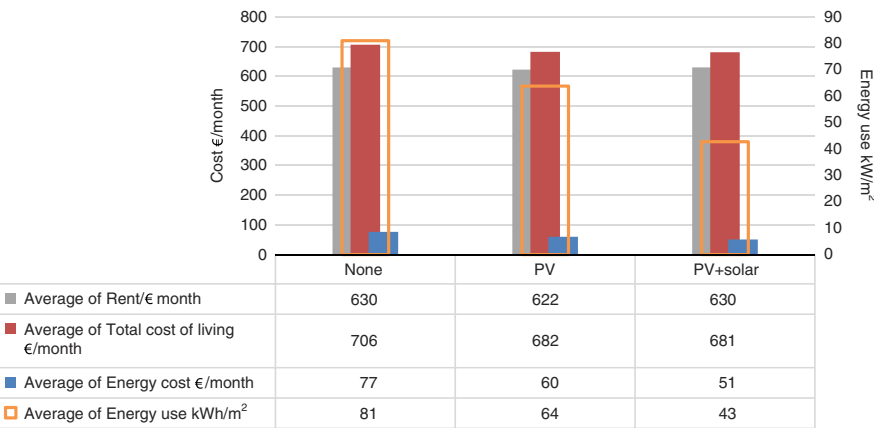


Figure 10.
Overview of the renewable energy option applied in DC1, in terms of energy cost, rent, the total cost of living and energy use



- (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 influences the cost of living. Out of the three options tested, the pellet boiler is 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 options 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 it gives a holistic standpoint to the issue of energy upgrades, by quantifying the effect of the potential measures for the whole exploitation period. The cost as a key – if not the most decisive – factor is put into perspective 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 measures do not have the objective of highlighting the differences 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 results 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.

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.

References

- Abreu, M.I., Oliveira, R. and Lopes, J. (2017), "Attitudes and practices of homeowners in the decision-making process for building energy renovation", *Procedia Engineering*, Vol. 172, pp. 52-59, available at: www.sciencedirect.com/science/article/pii/S1877705817305222.

- AEDES (2018), "Routekaart CO2-neutraal 2050: alle gegevens op een rij (Roadmap CO2-neutral 2050: all data at a glance)", available at: www.aedes.nl/artikelen/bouwen-en-energie/energie-en-duurzaamheid/instrumenten/routekaart-co2-neutraal.html (accessed 20 January 2018).
- Artola, I., Rademaekers, K., Williams, R. and Yearwood, J. (2016), *Boosting Building Renovation: What Potential and Value for Europe?*, Policy Department A: Economic and Scientific Policy, European Parliament, Brussels.
- Baumhof, R., Decker, T., Röder, H. and Menrad, K. (2018), "Which factors determine the extent of house owners' energy-related refurbishment projects? A motivation-opportunity-ability approach", *Sustainable Cities and Society*, Vol. 36, pp. 33-41.
- Boess, S. (2015), "Framing resident acceptance of sustainable renovation", Participatory Innovation Conference 2015, The Hague.
- BPIE (2011), *Europe's Buildings Under the Microscope*, Building Performance Institute Europe, Brussels.
- BPIE (2013), *Boosting Building Renovation: An Overview of Good Practices*, Building Performance Institute Europe, Brussels.
- BW7:220 (2016), "Burgerlijk Wetboek Boek 7: Bijzondere overeenkomsten (Civil Code Book 7: Special agreements)", Overheid.nl, available at: http://wetten.overheid.nl/BWBR0005290/2016-04-01#Boek7_Titeldeel4_Afdeling3_Artikel220 (accessed 20 August 2018).
- Bystedt, A., Östman, L., Knuts, M., Johansson, J., Westerlund, K. and Thorsen, H. (2016), "Fast and simple – cost efficient Façade Refurbishment", *Energy Procedia*, Vol. 96, pp. 779-787.
- CBS (2017), "Nederland in cijfers (the Netherlands in figures)", available at: <https://opendata.cbs.nl/statline/#/CBS/nl/> (accessed 1 December 2017).
- CO2-emissiefactoren (2017), "Lijst emissiefactoren (list of emission factors)", available at: <https://co2emissiefactoren.nl/lijst-emissiefactoren/> (accessed 30 April 2018).
- Conci, M., Konstantinou, T., Van Den Dobbelsteen, A. and Schneider, J. (2019), "Trade-off between the economic and environmental impact of different decarbonisation strategies for residential buildings", *Building and Environment*, Vol. 155, pp. 137-144, available at: www.sciencedirect.com/science/article/abs/pii/S0360132319302136.
- Crawford, K., Johnson, C., Davies, F., Joo, S. and Bell, S. (2014), *Demolition or Refurbishment of Social Housing? A Review of The Evidence*, UCL Urban Lab and Engineering Exchange for Just Space and the London Tenants Federation, London.
- Davies, P. and Osmani, M. (2011), "Low carbon housing refurbishment challenges and incentives: architects' perspectives", *Building and Environment*, Vol. 46 No. 8, pp. 1691-1698.
- DesignBuilder (2012), *DesignBuilder. 3.0.0.064 ed.*, DesignBuilder Software Ltd, Stroud.
- DIRECTIVE/844/EU (2018), *On the Energy Performance of Building*, The European Parliament and of the Council, Brussels.
- Domingo-Irigoyen, S., Sánchez-Ostiz, A. and Miguel-Bellod, J.S. (2015), "Cost-effective renovation of a multi-residential building in Spain through the application of the IEA Annex 56 methodology", *Energy Procedia*, Vol. 78, pp. 2385-2390, available at: www.sciencedirect.com/science/article/pii/S1876610215019268.
- EcoQuaestor (2014), *EcoQuaestor: de aanpak van Bouwprojecteconomie (EcoQuaestor: The Approach to Building Project Economy)*, EcoQuaestor, Roosendaal.
- EN15603 (2008), *Energy Performance of Buildings – Overall Energy Use And Definition of Energy Ratings*, European Committee for Standardization (CEN), Brussel.
- Filippidou, F., Nieboer, N. and Visscher, H. (2016), "Energy efficiency measures implemented in the Dutch non-profit housing sector", *Energy and Buildings*, Vol. 132, pp. 107-116.
- Guerra-Santin, O., Boess, S., Konstantinou, T., Romero Herrera, N., Klein, T. and Silvester, S. (2017), "Designing for residents: building monitoring and co-creation in social housing renovation in the Netherlands", *Energy Research & Social Science*, Vol. 32, pp. 164-179, available at: <https://doi.org/10.1016/j.erss.2017.03.009>.

- IEAAnnex56 (2012), “Cost effective energy and carbon emissions optimization in building renovation”, available at: www.iea-annex56.org/ (accessed 23 November 2015) .
- Konstantinou, T. and Dimitrijević, B. (2018), “Sustainable refurbishment for an adaptable built environment”, in Kosanović, S., Klein, T., Konstantinou, T., Radivojević, A. and Hildebrand, L. (Eds), *Sustainable and Resilient Building Design: Approaches, Methods and Tools*, TU Delft Open, Delft, pp. 206-227.
- Konstantinou, T., Guerra-Santin, O., Azcarate-Aguerre, J., Klein, T. and Silvestersacha, A. (2017), “Zero-energy refurbishment solution for residential apartment buildings by applying an integrated, prefabricated façade module”, *PowerSkin Munich*, Delft Open.
- Kumbaroğlu, G. and Madlener, R. (2012), “Evaluation of economically optimal retrofit investment options for energy savings in buildings”, *Energy and Buildings*, Vol. 49, pp. 327-334.
- Matschoss, K., Atanasiu, B., Kranzl, L. and Heiskanen, E. (2013), “Energy renovations of EU multifamily buildings: do current policies target the real problems?”, in Bjørnstad, E. and Economidou, M. (Eds), *Rethink, Renew, Restart. ECEEE 2013 Summer Study*, Berg Publishers, Toulon/Hyères.
- NEN (2017), *Investerings- en exploitatiekosten van onroerende zaken – Begripsomschrijvingen en indeling (NEN 2699) (Investment and Operating Costs of Property – Terminology and Classification)*, Normalisatie-instituut, Delft.
- Oorschot, L., Spoormans, L., El Messlaki, S., Konstantinou, T., Jonge, T.D., Oel, C.V., Asselbergs, T., Gruis, V. and Jonge, W.D. (2018), “Flagships of the Dutch welfare state in transformation: a transformation framework for balancing sustainability and cultural values in energy-efficient renovation of postwar walk-up apartment buildings”, *Sustainability*, Vol. 10, p. 2562.
- Priemus, H. and Elk, R.S.F.J.V. (1971), *Niet-Traditionele Woningbouwmethoden in Nederland*, Samsom, Alphen a/d Rijn.
- RVO (2015), “Nul op de meter”, Rijksdienst voor Ondernemend Nederland, available at: www.rvo.nl/onderwerpen/duurzaam-ondernemen/gebouwen/technieken-beheer-en-innovatie/nul-op-de-meter (accessed 1 April 2018).
- Santangelo, A. and Tondelli, S. (2017), “Occupant behaviour and building renovation of the social housing stock: current and future challenges”, *Energy and Buildings*, Vol. 145, pp. 276-283.
- SER (2013), *Energieakkoord Voor Duurzame Groei*, Sociaal-Economische Raad, Den Haag.
- Sijphee, N.C., Borsboom, W.A. and Opstelten, I.J. (2016), “Results from first ‘NetZero energy’ projects in the Netherlands”, in Opstelten, I., Rovers, R., Verdeyen, N. and Wagenaar, A. (Eds), *Sustainable Built Environment 2016: Transition Zero – SBE16*, HU University of Applied Sciences Utrecht, Utrecht.
- Stroomversnelling (2013), “Maak de stroomversnelling mee”, available at: www.stroomversnelling.net/over-stroomversnelling/ (accessed 23 November 2015).
- Van der Werf, E.N.M. (2011), “Bewonersbelangen bij renovatie in bewoonde staat”, Master, Delft University of Technology, Delft.
- WMDwater (2016), “Hoeveel water gebruiken we per dag?”, available at: www.wmd.nl/over-wmd/nieuws/archief-nieuwsbrieven/nieuwsbrief-december-2013/hoeveel-water-gebruiken-we-dag (accessed 20 August 2018).

Corresponding author

Thaleia Konstantinou can be contacted at: t.konstantinou@tudelft.nl

Acknowledgment

This paper forms part of a special section “Technical innovations in smart and sustainable built environments”, guest edited by Rob Roggema.

For instructions on how to order reprints of this article, please visit our website:

www.emeraldgrouppublishing.com/licensing/reprints.htm

Or contact us for further details: permissions@emeraldinsight.com