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PLEASE CITE THE PUBLISHED VERSION

PUBLISHER

Elsevier

VERSION

AM (Accepted Manuscript)

PUBLISHER STATEMENT

LICENCE

REPOSITORY RECORD

Multi-Criteria Assessment Approach for a Residential Building Retrofit in Norway

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Abstract: This paper presents a multi-criteria assessment approach for a wide range of energy efficient measures and their combinations applied for a residential building retrofit in Norway. A number of passive, active and renewable energy efficient measures (EEMs) have been selected and defined. Based on the level of energy saving potentials, these EEMs have been combined into 18 retrofit combination packages (COMBs) and grouped into various retrofit levels (Moderate Retrofit-I, II, III and Extensive Retrofit). The annual primary energy consumptions (heating, hot water and electricity) for the proposed combination packages were simulated in IESVE building energy simulation software. This is then followed by two levels of assessments: i) the comprehensive assessments of the key retrofit priorities including primary energy reduction, global costs, payback period and the carbon emission reduction and ii) social assessment with the aim to represent various stakeholders' views on the selected COMBs using a metric of weighting factors. Based on this, a multi-criteria assessment approach featuring a novel ranking factor (EEES) taking into account of energy, economic, environmental and social

30   aspects during retrofit process was adopted. This approach quantifies different stakeholders'

31   perspectives on the proposed COMBs, which could enable various stakeholders' involvement

32   in the retrofit decision making process. It was concluded that COMB 05 and 06, which include

33   only 2-3 passive and active EEMs have been ranked and chosen as the most favourable retrofit

34   solutions, with EEES value equalled to 25.6 from various stakeholders' perspectives. The

35   impacts of changing renewable energy prices and PV generated feed-in tariff rates on the global

36   costs, carbon reductions and primary energy consumptions of the proposed COMBs, which

37   have rarely been analysed in literature, are numerically investigated in this research. Such

38   renewable EEMs which are greatly recommended by the European Commission, are expected

39   to gain further support from national level government renewable incentives. Therefore, it is

40   envisaged that in the long term, Extensive Retrofits incorporating mostly renewable EEMs

41   could become more affordable and cost effective.

42   **Keywords:** Building retrofit, cost-optimal analysis, carbon emission, social assessment,

43   multi-criteria approach

1.   Introduction

45   The Intergovernmental Panel on Climate Change (IPCC) reported that there has been an

46   approximate 1.0°C global temperature rise, since the pre-industrial era due to human activities

47   [1]. They claim that if the current trend continues, global temperatures will rise by additional

48   1.5°C between the year 2030 and 2052. The Eurobarometer report on climate change, which

49   was published in September 2017, states that 74% of European Union citizens consider climate

50   change as a very serious problem and 92% of European citizens consider it as a serious problem

51   [2].

52   Johansson et al. [3] state that buildings are responsible for 30 – 40 % of global carbon emissions

53   and that there is a high potential for energy savings in the building sector. The International

54   Energy Agency (IEA) points out that making improvements in the energy efficiency of the

55   housing stock could play a significant role in mitigating climate change and achieving energy

56   system objectives [4]. Reducing greenhouse gas emission by applying energy efficiency

57   solutions in the building retrofit process have been widely studied as an effective method to

58   tackle the global warming challenge. In order to achieve European Union's policy goals, the

59   rate of retrofitting has to increase from its current levels of 0.5% – 1.5% to around 2.5% – 3%

60   of the housing stock per year [5, 6]. Rosenow et al. [7] and Wilson et al. [8] state that up to 50%

61   of the energy used in households could be saved by implementing energy efficient retrofits and

62   other measures depending on policies that support decision making in the households [6]. A

63   significant reduction in energy consumption in the European Union can be achieved by

64   upgrading existing European buildings, since the existing building stock has low efficiency [8].

Most existing research works are focused on the investigation of potential energy savings and the economic aspects of the selected conventional energy retrofit measures (related to building fabric retrofits [9-13]) in Northern [14-19] and Southern [20-22] parts of Europe. Ciulla et al. [11] investigated the energy saving and economic impact for two typical buildings in four Italian cities. However, only basic retrofit measures related to building fabric (insulation and window replacing) were considered in this study. Similarly, Nicolae and George-Vlad [23] applied life cycle and thermal performance assessment of three external wall insulation materials for a building retrofit in Galati, Romania. Historical buildings in Italy [11, 24] and Portugal [10] were renovated by using a cost-optimal method considering energy, environmental and economic impacts of selected retrofit packages. A historic wooden apartment in Estonia [14] has been upgraded with external wall insulation, energy efficient window, heat recovery and an air to water heat pump. The authors concluded that the cost optimal primary energy consumption of 250kWh/(m^2 a) could be achieved in the case study historical wooden building. In the study of Ascione et al. [21, 25], a number of cost-optimal retrofit packages were defined by considering both limitless economic availability and limited budget for a hospital building in Italy. The optimized results indicated a reduction of primary energy consumption up to 67.9kWh/(m^2 a) with global costs reduction of 24.5%. Static and dynamic simulation models have been established for predicting pre and post retrofit energy consumptions of a historical building in Ireland [15]. The results showed that 55.6% energy reduction could be achieved using selected deep retrofit measures.

The promotion of on-site renewable energy utilization has also been widely considered by researchers, with the aim to achieve the strict energy saving targets (i.e. 40% greenhouse gases reduction by 2030) for the building sector set by Energy Performance of Building Directive (EPBD) [26]. Lopez and Frontini [27] conducted a historic building retrofitting project incorporating solar photovoltaics (PV) and a solar thermal system to improve energy performance and the level of comfort for 3 buildings in Switzerland. Eicker et al. [28, 29] performed a cost effectiveness analysis of 3 demo buildings in Italy, Portugal and the UK. The economic benefits and the primary energy consumption for various configurations of two renewable technoogies (solar PV and solar thermal collectors) were investigated parametrically. Evola et al. [30] investigated the integration of BIPV into a social housing project in Italy for 3 different cities (Milan, Rome, Catania). The effects of building orientation and the characteristics of three different types of PV modules and PV size and costs were considered. Combined heat and power (CHP) was adopted by Santoli et al. [31] for the integration of bioenergy production with the Bari airport refurbishment project. The study analysed three bioenergy production resources using discounted cash flow method. Hybrid system integration for historical building retrofit was performed by Basso et al. [32], which

101   included six different combinations of CHP (combined heat and power), PV (photovoltaics),

102   PV/T (solar hybrid collectors), electric heat pumps, transcritical CO_2 heat pumps and gas heat

103   pumps. The optimal renewable to primary energy ratio was proposed by Sharafi et al. [33] with

104   the aim to achieve the optimized algorithms between energy saving, net present value and

105   carbon emission. Nizetic et al. [34] proposed various hybrid energy options (wind, solar PV,

106   fuel cell, etc.) for the residential application of heat pump integrated cooling system for

107   Mediterranean climatic conditions. The authors concluded that the heat pump with heat

108   recovery system showed better energy efficiency compared with other solutions.

109   In general, the final retrofit solution is not always the case of selecting the most cost-effective

110   combination measures with the highest energy saving and lowest carbon emissions. The

111   decision making process for building retrofit can take into considerations the stakeholders'

112   (designers, tenants, landlords, local government and policy makers) preferences, since

113   stakeholders evaluate retrofitting processes differently according to their roles, experiences and

114   needs. Stakeholder's satisfaction has gained increasing importance in measuring success of

115   projects, in addition to the so-called the "iron" triangle: time, cost and quality. Construction

116   related projects are not exceptional in this regard. Identifying stakeholders' preferences plays a

117   pivotal role in devising suitable efforts to ensure stakeholder satisfaction [35]. It is therefore

118   very crucial to establish a practical and user friendly multi-criteria assessment approach to

119   capture various stakeholders' preferences on proposed combination measures, as this could

120   greatly facilitate the final decision making process. The literature review shown in Table 1

121   highlights that most of the current research is only focused on the assessment of energy [10, 20,

122   23], carbon emission [10, 18] and cost [11, 18, 36-39]. Analysis taking into account

123   stakeholders' preferences in the retrofit decision making process is restricted in the context of

124   using matrix for the evaluations of different social aspects [36], without linking them with the

125   relevant energy, economic and environmental analysis. Moreover, most of this research has

126   concentrated solely on the impact of individual renewable energy sources (solar PV [27, 32]

127   and solar thermal collector [37, 39]) on the energy saving potential. Research evaluating the

128   impacts of integrating conventional retrofit measures with the renewable energy measures on

129   the energy saving, economic, environmental and social benefits is hardly performed and

130   therefore deserves more attention.

131   In this research work, a typical residential apartment constructed in 1990s in Oslo (Norway)

132   has been selected as the case study building. The proposed research aims to bridge the current

133   research gaps and propose the following key research methodologies: 1) based on European

134   Union's building energy saving categories [36],18 retrofit combination packages (COMBs)

135   incorporating different levels of passive, active and renewable EEMs are firstly classified and

136   grouped in to four categories (minor retrofits, moderate retrofits, extensive retrofits and

137 almost zero-energy building retrofits), which corresponds to energy consumption reduction in

138 the range of 0-30%, 30-60%, 60-90% and beyond. A key target of this research is to integrate

139 commercially available renewable energy measures (Ground Source Heat Pump, solar PV,

140 solar thermal collector) with conventional passive and active energy measures and investigate

141 the overall energy saving potentials, economic benefits and carbon reductions. Based on this,

142 a multi-criteria assessment energy, economic, environmental and social (EEES) ranking

143 factor has been adopted, as a complementary method to evaluate different stakeholders'

144 perspective on the proposed combination packages. The implementation of this multi-criteria

145 assessment approach will greatly facilitate the retrofit decision making process with ease and

146 wider engagement from various stakeholders. 2) with the renewable energy incentives

147 prompted by European Commission, the material and manufacturing costs of the renewable

148 energy products are expected to drop drastically in the future. The impacts of changing

149 renewable energy prices and PV generated feed in tariff rates on the global costs, carbon

150 reductions and primary energy consumptions, which have rarely been studied in literature, are

151 numerically investigated in this research.

Table 1 Summary of the latest published literature related to cost-effectiveness, carbon emission and social impact analysis

Reference	Building type	Vintage and location of building	Selected energy retrofit measures	Optimization approach	Life cycle analysis parameters	Carbon emission analysis (équivalant carbon emission factor)	Social impact analysis	Conclusion
Liu et al.[18]	Residential apartment building	1890s, Stockholm, Sweden	Insulation (attic, wall, basement), glazing and heating system upgrading	Life cycle cost method	Discount rate: 1%, 5%, 9%;	District heating: 0.124tCO2/MWh; Electricity: 0.74tCO2/MWh	NA	The impact of the variations of discount rate was less important compared with changing electricity price.
Sahin et al. [20]	Historical hotel	1920s, Izmir, Turkey	Insulation (attic, wall, basement), glazing and heating system upgrading, indoor temperature control	Transdisciplinary approach	NA	NA	Heritage values, durability, moisture, indoor environment	Considering the preservation of historical heritage, about 30% of energy saving could be achieved.

Ciulla et al. [11]	Historical building	Cagliari/ Roma/ Milano/ Palermo, Italy	Insulation (roof, external wall), glazing upgrading,	Cost-optimal method	NA	NA	NA	The primary energy saving could reach 44.6% and 56.7% for two building base cases.
Tadeu et al [10]	Historical building	Beginning of 20th century, Portugal	Insulation (roof, external wall), glazing upgrading, heating and domestic hot water upgrading	Cost-optimal method	Discount rate: 6%, 12%; Life time: 30 years	Natural gas: 0.202tCO2/MWh Electricity: 0.36 tCO2/MWh	NA	The optimal insulation thickness were 50mm to 120mm, using economic assessment.
Nicolae and George-Vlad[23]	School building	Galati, Romania	Three selected external wall insulation materials	Cost-optimal method	NA	NA	NA	The selected external insulation retrofit could lead to 55% less energy consumption compared with baseline case.
Shao et al. [37]	Office building	1900, Aachen, Germany	Insulation (basement, wall), glazing and heating system upgrading, air	Multi-objective optimization	NA	NA	NA	This multi-objective optimization presented a suitable research method to consider the

			tightness improvement					stakeholder's requirement during building retrofits.
Araujo et al. [38]	Residential building	Northern Portugal	Insulation (basement, wall), glazing and heating system upgrading, shutter and curtain, HVAC upgrading, solar collector	Cost effectiveness method	Discount rate: 1%-6%; energy price variation: ±3%	NA	Investment willingness of the stakeholders.	This analysis studied and presented a cost-benefit ratio, which leads to the optimal selection of energy efficient solutions.
Arumagi et al. [39]	Historical wooden apartment	1920s, Estonia	Insulation (attic, wall), glazing upgrading, ventilation with heat recovery, air to water heat pump	Cost-optimal method	Discount rate: 4%; energy price escalation: 3%	NA	NA	The economic analysis showed that the optimal PE of $250kWh/(m^2 a)$ for the selected wooden historical building.
Niuemela et al. [40]	Residential apartment building	Helsinki, Finland	Insulation (attic, wall, basement), glazing and heating system upgrading, PV, solar collector, ventilation system	Cost-optimal method	Discount rate: 3%energy price escalation: 2%, life cycle period: 30 years	Electricity: $0.209tCO2/MWh$; CHP: $0.183tCO2/MWh$	NA	Energy saving of 90-98€/m^2, primary energy reduction around 850-930kWh/m^2 could be achieved.

2. Methodology

The research methodology applied for the proposed work is illustrated in Figure 1. The retrofit process can be classified into 3 stages: pre-retrofit, retrofit design and post-retrofit stage. During the pre-retrofit stage, building survey and physical monitoring were conducted in order to define the existing baseline building conditions and energy utilization situations. Social analysis including the residents' survey and the examination of the local regulations was conducted. During this stage, various social aspects including the local government planning permission, landlord/residents' preference, affordability and willingness towards certain energy measures were summarized and used as input for the design stage. In the retrofit design stage, based on the survey results and energy utility situation, the building baseline model was established and validated in IESVE building energy simulation software. A retrofit technology library was established with the detailed technology specification and costs provided by the Rezbuild project technology providers [40]. This was used to define and apply the individual energy efficient measures (EEMs) and their combination packages into the baseline model to perform the energy performance assessment. The next step was to conduct a cost optimal assessment and carbon emission calculation. Based on this, an assessment approach using a novel energy, economic, environmental and social (EEES) ranking factor was developed and adopted. This provides numerical evaluations from multi-criteria perspectives for the proposed combination packages. In the post-retrofit stage, the physical monitoring and Return of Investment (RoI) calculation will be performed to demonstrate the economic, social and environmental benefits for the proposed building retrofit plan compared with the baseline scenario. The multi-criteria assessment approach could be used as good practice guideline for other building retrofit projects in the Scandinavian Region and beyond.

2.1 Demo building survey

This research is derived from EU Horizon 2020 funded project RezBuild [41], which aims to achieve fast and efficient building retrofits for selected three demo site buildings in Norway, Italy and Spain. The research presented in this paper will focus on the building retrofits for a residential apartment building (as shown in Figure 2) in Oslo, Norway. In urban areas, the number of apartment dwellings is significantly higher than the national average. Such residential apartment in Oslo region accounts for around 50% of the settlement patterns [42]. Constructed in 1990s, this demo site building represents typical dwelling types in Norway that have been in service for more than 20 years and now urgently needs energy retrofit. The demo site building is located at the Bertramjordet condominium in Rosenholmveien (14km from Olso centre). The Bertramjordet complex consists of 4-5 storey apartment buildings and townhouses. The selected demo building is apartment block No.64 in this area, with a total floor area of

36 $1839.4m^2$ (heated floor area of $934.2m^2$ and unheated floor area of $905.2m^2$). The residents

37 living in this community are mainly low-income family and pensioners.
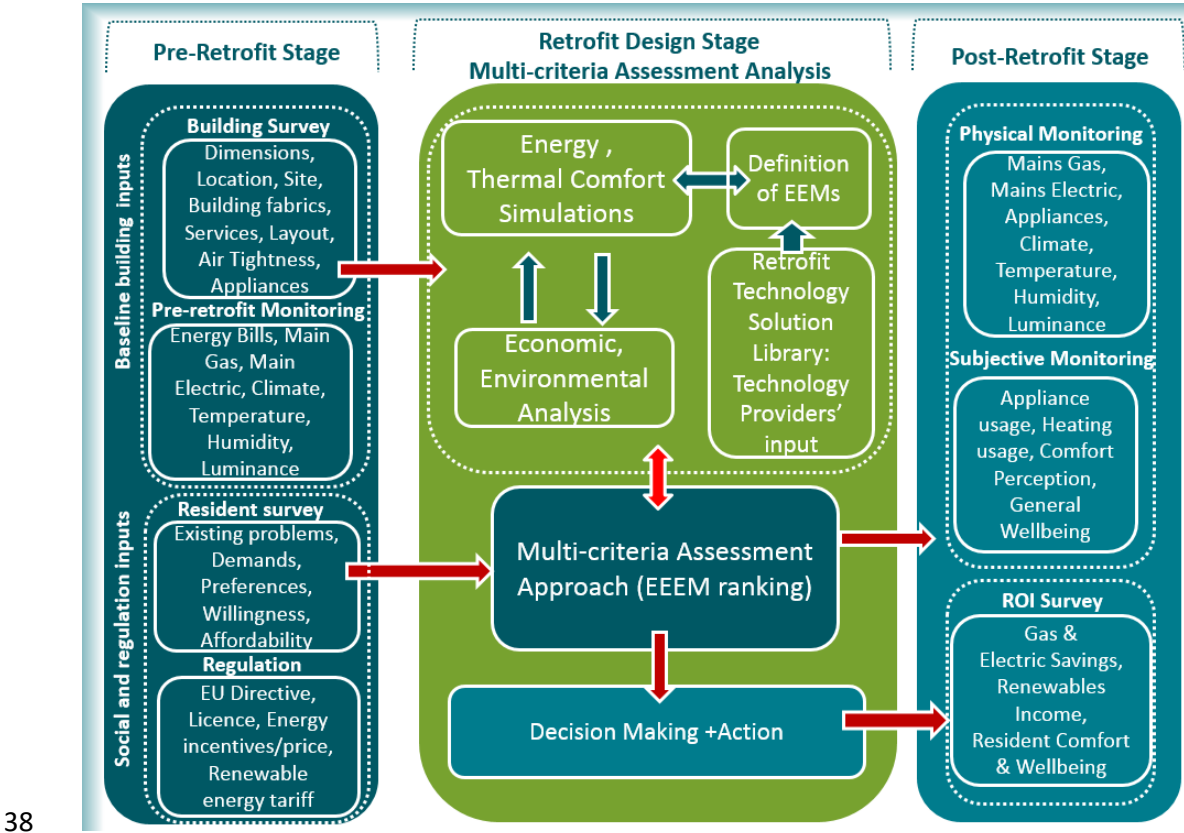

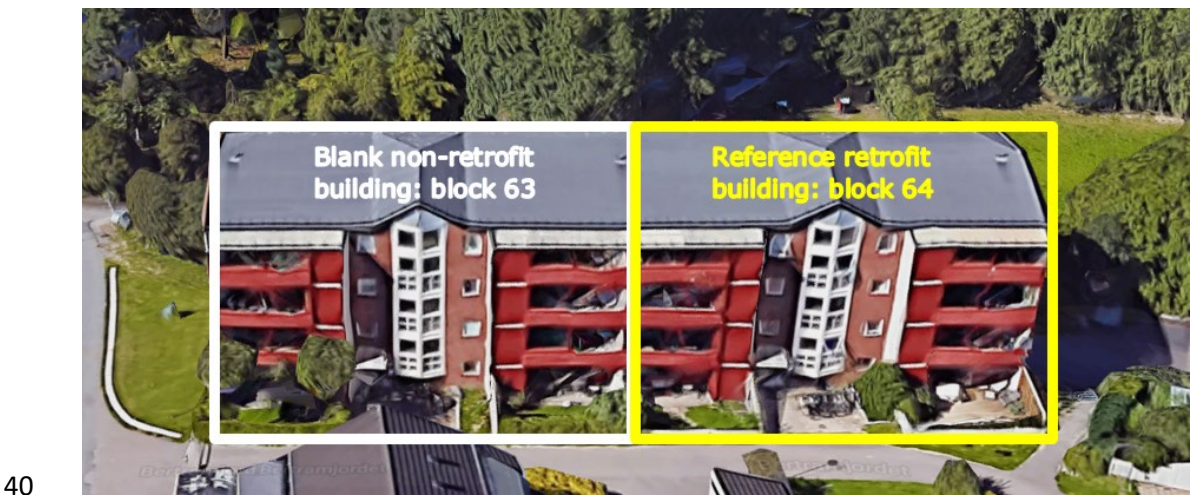39 Figure 1 Schematic representation of the proposed research methodology

41 Figure 2 Southeast view of the demo site building

42 **2.2 Building condition characterization**

43 **Building fabric conditions:** Several site inspections, surveys and residents group meetings

44 with the Bertramjordet cooperatives [43] were conducted by RezBuild project partner OBOS

10

45 [44] from autumn 2016 to March 2017. The site survey showed that the external walls typically

46 had a thickness of 280mm with one layer of thermal insulation as detailed in Table 1. The

47 foundation was constructed of poured reinforced concrete with variable thickness. The attic

48 floor consist of a mixture between mineral wool and reinforced concrete, each of 200mm

49 thickness. The detailed building characteristics and the U values of building envelopes are listed

50 in Table 1. The entire apartment building is connected with the district heating system, which

51 generates heat by combustions of biomass wastes. The current district heating system in the

52 baseline model was considered running 24-7 at a constant room temperature of around 21℃.

53 **Occupancy behaviours:** A pre-retrofit occupancy survey carried out by RezBuild project

54 revealed that the current building occupancy is a mixture between retired pensioners and

55 families with children. The occupancy profile was defined with the heating system on during

56 the winter season (from 1st September to 30th May). The current heating system sometimes

57 cause overheating problems to the residents, who kept the windows open for natural ventilation

58 during winters. This will potentially leads to great amount of unnecessary heating energy

59 consumption.

60   Table 1 Building characteristics and the U value of building envelopes

Building component	Material (from outside to inside)	Total thickness (mm)	U-value (W/m^2K)
Roof	concrete tiles, fibreboard, membrane	156	0.89
Attic Floor	mineral wool	420	0.18
External gamble wall	reinforced concrete wall, mineral wool	280	0.32
External balcony wall	studwork wall , gypsum, mineral wool, laths and horizontal cladding	160	0.23
Glazing	double layer glazing		3.13
Basement floor	lightweight metallic cladding,	270	0.50

	Urea-formaldehyde (UF) foam, Brickwork		
Basement ceiling	lightweight metallic cladding, steel, felt/bitumen layer	15	5.98
Basement external wall	reinforced concrete wall	280	3.43

2.1 Baseline model establishment

Detailed energy modelling and performance assessment is crucial for accurately simulating the building energy consumption and saving potentials for selected energy measures, taking into account of the interactions between various parameters (building fabric details, climatic conditions, existing building service system). Hence, the demo building baseline model (as shown in Figure 3) was established in IESVE software. The available annual energy consumption bills for Bertramjordet condominium were used to validate the established model (Table 2). The baseline building simulation is carried out according to the following input parameters defined from ASHRAE and CIBSE guide: indoor temperature ($\geq 21^\circ$C); mechanical ventilation rate (0.85ACH); infiltration rate (0.6ACH); occupant internal gains (90.0W/person of sensible heat, 60.0W/person of latent heat); lighting and electric device consumption (4.4W/m^2); district heating efficiency 80%; district heating mode (01 Sep to 31 May). For outdoor weather condition, the weather data of Oslo acquired from EnergyPlus is applied.

Figure 3 Baseline model of the demo site building in IESVE

Table 2 Monitored and calculated district heating energy

	2014	2015	2016
Annually monitored overall district heating energy (kWh)	118830	119682	125819
Annually monitored specific district heating energy (kWh/m^2)	127.2	128.1	134.7
Calculated district heating energy in building energy model (kWh/m^2)	129		

80

2.2 Energy performance assessment

2.3.1 Identification of individual energy efficient measures

For the demo site building retrofit in Oslo, three levels of energy efficient measures (EEMs) are identified: passive, active and renewable energy EEMs.

- Passive EEMs are related to the retrofit measures made to the existing building fabric conditions, such as retrofits of external wall, upgrading the existing window, green roofs for increasing the building sustainability [45, 46].
- Active EEMs include upgrading the building service system and energy saving control strategies to reduce the energy consumption, such as installation of lighting sensors, efficient lighting system, improving the air tightness of the building and smart building management system for temperature/space heating/cooling control.
- Renewable EEMs covering the utilization of renewable energies including solar PV, solar thermal collector and ground source heat pump.

Based on the building survey results and the obtained baseline building energy consumption condition, 5 passive EEMs, 3 active EEMs and 3 renewable EEMs have been defined and with the technical specifications shown in Table 3. All the technical specifications and product costs were obtained from the RezBuild project partners (see website [47]), available product manufacturers or technology developers. The investment costs summarized in Table 2 include design, product manufacture, connections to the supplier and installation/commissioning, 24% of VAT tax have been considered as Norway standard tax rate.

Table 3 Individual energy efficient measures, the associated technical specifications and costs

	Nomenclature	Energy efficient measures (EEMs)	Technical specification	Investment costs	Maintenance costs	Replacement costs
Passive measures	GR	Glazing retrofit-triple glazing	U=0.62W/m²K Triple glazing windows	€282.5/m²	NA	NA

	GI	Garage ceiling insulation upgrading	U=0.1W/m²K, d= 50mm Vacuum insulation panel	€203.4/m²	NA	NA
	AI	Attic floor insulation upgrading	U=0.1W/m²K, d= 50mm Vacuum insulation panel	€203.4/m²	NA	NA
	WI	Wall insulation upgrading	U=0.1W/m²K, d= 50mm Vacuum insulation panel	€310.8/m²	NA	NA
	AT	Air tightness improvement	EPDM foil system	€22.0/m²	NA	NA
Active measures	HR	Heat recovery system	Effectiveness: 86%	€42,375.0	NA	NA
	SP	Set point temperature sensor	Temperature set decrease to 21℃ in winter	€4,746.0	NA	NA
	ED	Efficient lighting device	LED lighting with 40% electricity reduced	€2,689.4	NA	NA
Renewable energy measures	GSHP	Ground source heat pump	GMDW 18 plus: heat capacity of 18.7 kW Operation point: B0/W50, COP: 3.4	€28,2500.0 component costs(30kW)+ €21,244.0 installation costs+ €12,204.0 Vertical Borehole construction costs	0.6% of the investment costs [40]	Over 30 years, Replacement factor=0.41 [48]
	ST	Flat solar thermal collector for DHW	A=172.8m², Tilt angle 25° Solar heat generation efficiency: 47% Azimuth 135° (from the North) Azimuth 315° (from the North)	€655.4/m² including all the components and installation costs	2% of the investment costs[40]	Over 30 years, Replacement factor=0.41 [48]
	BIPV	Building Integrated Photovoltaics	A=192m^2, Tilt angle 25°, 28.9kW_p (test standard) Electricity generation efficiency:18.8% Azimuth 135° (from the North) Azimuth 315° (from the North)	€299.5/m² including all the components and installation costs	2% of the investment costs[40]	Over 30 years, Replacement factor=0.41 [48]

102

103 **Glazing (GR):** Most of the existing windows in the demo site building are double glazing with

104 the average U value of 3.13 $W/(m^2 \cdot K)$. According to the Norwegian passive house standard

105 of TEK 17[49], the U-value of the windows including frames should be less than 0.8W/($m^2 \cdot$

106 K) for residential apartment. As suggested and agreed by the residents, a triple-glazing window

107 with U-value of 0.62W/($m^2 \cdot$ K), is chosen for glazing retrofit. The selected glazing retrofit

108 (GR) has a total thickness of 48mm (8mm glass + 10mm air cavity +10mm glass + 10mm air

109 cavity + 10mm glass) with visible light normal transmittance of 0.76 and g-value of 0.68.

Insulation (GI/AI/WI): The demo site building envelope has good thermal insulation layers
with an average U-value of $0.3\ W/(m^2 \cdot K)$. However, this value does not comply with the
Norwegian passive house standard of TEK 17 [49], with the indication of less than $0.1\ W/(m^2 \cdot K)$ for residential building envelope. Advanced insulation materials of vacuum insulation
panels (VIP) manufactured and provided by RezBuild project partner Saint-Gobain Ltd. is
chosen as the additional insulation materials. VIP with thickness of 75mm is chosen for the
retrofit of garage ceiling (GI) and attic floor (AI), while the VIP with 80mm and 55mm
thickness will be applied in balcony wall and external wall (WI) respectively.

Air tightness (AT): To comply with the 2013 Part L Building regulations [50] and TEK17
Norwegian passive house standard [49], the air infiltration rate should be less than 2.5 ACH at
50 Pa pressure difference. Therefore, EPDM foil system from Castelein Sealants NV Company
[51] is selected to reduce the air infiltration rate from 0.6ACH to 0.35ACH.

Mechanical ventilation with heat recovery (HR): the existing ventilation systems rely on the
extraction fans, with the measured air flow rates in kitchens and bathrooms of 30L/s and 15L/s,
respectively. A mechanical ventilation with heat recovery system (HR) will be incorporated as
one of the active measures for the existing building service systems. With the installation of
HR, fresh air will be drawn in with exhaust fans passing through the heat exchanger, where the
fresh air from the outside will be preheated by the exhausted air from the room. In this measure,
HR is designed with 86% effectiveness of heat recovery.

Automatic temperature control system (TP): According to ASHARE standard [52] and
passive house standard in Norway [49], the suggested maximum and minimum temperature
and relative humidity range are 26℃, 20℃ and 30-60% for residential building blocks.
Therefore in this study, the indoor set temperature will be controlled by BOASH heating starter
kit with constant indoor temperature of 21℃ during winter heating seasons.

Efficient lighting (ED): The current demo site building is equipped mostly with compact
fluorescent lighting (CFL) bulbs. However, with the advancement of efficient lighting
technologies, LED lighting bulbs are 50% more efficient than the CFL. Therefore, efficient
dimming lighting will be adopted as one of the active measures, which can achieve a total of
40% lighting energy saving compared with existing CFL bulbs with 3% internal gain reduction.

Ground Source Heat Pump (GSHP): The existing district heating system driven by biomass
waste heat has two obstacles. Firstly, over the years, the degradation of the pipelines has
resulted in reduced overall heating performance. The upgrading and maintenance work is

142　needed regularly to improve the energy supply efficiency. Secondly, the temperature condition

143　of the existing DH could not be controlled and adjusted by the occupants. During the pre-site

144　survey, the indoor overheating problem was observed which can only be solved by keeping the

145　window open to allow natural ventilation. The associated energy lost could be significantly

146　avoided by using a more energy efficient supply system such as GSHP. Due to the extreme cold

147　winter condition in Norway, borehole GSHP will be selected. In this simulation, the chosen

148　operation point of such GSHP is B0/W50 with COP of 3.4, the heat capacity of 18.7 KW and

149　power consumption of 5.5 KW under test standard of EN14511 [53].

150　**Solar thermal collector (ST)**: As obtained from baseline building simulation results, the

151　domestic hot water demand accounts for 15% of the total energy consumption. Considering the

152　daily hot water consumption of 57.6L/per person and the available roof surface area, the solar

153　thermal collector with a total surface area of $172.8m^2$ is proposed.

154　**Building intergraded photovoltaic (BIPV)**: Benefitting from a large pitched roof, the demo

155　site building can be equipped with BIPV system. The monocrystalline silicon based BIPV will

156　be manufactured and provided by RezBuild project partner ONYX Ltd. According to the

157　climatic data in IESVE, the calculated peak electricity generation rate can reach $28.9KW_p$. The

158　total installation area of PV panels is estimated to be around $192m^2$　with a tilt angle of 25°.

159　**2.3.2 Identification of retrofit combination packages**

160　Based on the defined various possible EEMs, 18 retrofit combination packages (COMBs)

161　incorporating different levels of passive, active and renewable EEMs are classified according

162　to the four categories specified by EU policy document . These four categories are: minor

163　retrofits, moderate retrofits, extensive retrofits and almost zero-energy building retrofits, which

164　corresponds to energy consumption reduction in the range of 0-30%, 30-60%, 60-90% and

165　beyond, respectively [36]. In the proposed research, Moderate Retrofit-I, II, III and Extensive

166　retrofit have been defined according to level and primary energy reduction, as shown in Table

167　4. Moderate Retrofit-I (combination packages COMB 01-04) focus on integrating passive only

168　EEMs into the baseline model. Moderate Retrofit-II (COMB 05-08) are dedicated to investigate

169　the combination between the selected active EEMs and passive EEMs. Moderate Retrofit-III

170　(COMB 09-12) includes 1 active EEMs with 1-2 renewable energy measure /passive measures.

171　Finally, the combinations between passive EEMs, active EEMs and at least 2 renewable EEMs

172　are grouped in Extensive retrofit (COMB 13-18).

173　　　　　　　　Table 4 Combination packages based on different retrofit levels

Retrofit Level	Combination package (COMB)	Passive measures					Active measures			Renewable energy measures		
		GR	GI	AI	WI	AT	HR	SP	ED	GSHP	ST	BIPV
Moderate Retrofit-I	COMB01	√	√	√								
	COMB02	√			√							
	COMB03		√	√	√							
	COMB04	√	√	√	√							
Moderate Retrofit-II	COMB05	√					√					
	COMB06					√		√	√			
	COMB07	√	√	√	√	√		√	√			
	COMB08	√				√	√	√				
Moderate Retrofit-III	COMB09	√				√		√		√		
	COMB10	√								√		
	COMB11						√			√		
	COMB12	√					√			√		
Extensive Retrofit	COMB13	√					√			√	√	
	COMB14	√					√			√	√	√
	COMB15	√					√			√		√
	COMB16	√				√	√	√		√		
	COMB17	√				√	√	√		√		√
	COMB18	√	√	√	√	√	√	√	√	√	√	√

174

2.3 Life cycle cost analysis and carbon emission calculation

2.4.1 Cost optimal method

As suggested by the European Directive on the energy performance in buildings (EPBD) [26], the "cost optimal" method will be applied in this research to establish the relationship between

179   the global costs and primary energy consumptions of the selected combination packages. The

180   best optimal measures will be those with the highest levels of energy savings and lowest global

181   costs. For the building sector, the total costs are defined as global costs $C_g(\tau)$, which takes in

182   to account of the initial investment costs of selected EEMs and the accumulated annual costs

183   over the life cycle period.

184   As a method for an economic assessment, the EPBD recast suggests the net present value (NPV)

185   for the calculation of global costs [54]. An appropriate calculation can be described by the

186   following formula:

187     $C_g(\tau) = C_I + \sum_j \left[\sum_{i=1}^{\tau} (C_{a,i}(j) \times R_d(i)) + C_{c,i}(j) - V_{f,\tau}(j) \right]$ Eq. (1)

188   Where

189     $C_g(\tau)$ is the global cost referring to starting year τ_o;

190   C_I is the initial investment costs;

191     $C_{a,i}(j)$ is the annual costs year I for energy related component j, which includes energy costs,

192   operational costs, periodic or replacement costs and maintenance costs;

193     $R_d(i)$ is discount rate for the year, which depends on the interest rate;

194     $C_{c,i}(j)$ is the accumulated carbon cost of greenhouse gas emissions due to the suggested

195   technology measures over the life cycle period;

196     $V_{f,\tau}(j)$ is the final value of component j at the end of the calculation period (referred to the

197   starting year τ_o). The disposal cost (if applicable) should be considered here.

198   As the maintenance, operating and energy costs are all related to the expenses in the future,

199   they will need to be calculated as present values according to the defined discount rate. The

200   discount rate $R_d(i)$ depends on the real discount rate R_r, and the year (n) of the considered

201   costs. The discount rate can be expressed as following:

202     $R_d(i) = \left(\frac{1}{1+R_r} \right)^n$ Eq. (2)

203   The real discount rate R_r is closely related to market interest rate R and inflation rate R_i, can
204   be calculated using following equation:

205     $R_r = \frac{R+R_i}{1+R_i}$ Eq. (3)

206   **2.4.2 Energy price, maintenance and operating costs**

207   As shown in Eq. (1), annual costs $C_{a,i}(j)$ include costs for energy carriers that cover the demand

208   for space heating and cooling, ventilation, domestic hot water and lighting, including auxiliary

209 energy. Income from produced energy (e.g. via photovoltaic systems) can be subtracted from
210 the costs for energy carriers. The service lifetime of measures should be set according to the
211 information set out in European standards (e.g. EN15459). The lifetime of the building elements
212 considered as following: thermal insulation (50 years), window and heat recovery system (30
213 years) and renewable energy sources (20 years).

214 According to the report from EPBD [48], residual value is considered only for thermal
215 protection measures (50 years lifetime period) with 40% value after 30 years of life cycle and
216 discounted to the beginning of the calculation period (16.5% residual value for discount rate of
217 3%). The maintenance costs for BIPV, GSHP, ST, are considered as 0.6%, 3.0% and 2.0% of
218 their investment costs respectively [48]. The replacement costs were considered only for
219 technical installations of BIPV, GHSP and ST by the use of a replacement factor of 0.41 (3%
220 discount rate) [48].

221   Table 5 Main parameter for the cost optimal analysis of the proposed research

Calculation period	30 years
Country	Norway
Electricity price	€0.09/kWh
District heating price	€0.09/kWh
Water usage price	€0.005/litre
Market Interest Rate	3.5%
Inflation rate	2.4%
Energy price escalation rate	2.8% for electricity and district heating [48]
Maintenance costs	0.6%, 3% and 2% of the initial investment costs for BIPV, GSHP, ST
Replacement factor	0.41
Residual costs	40% for thermal insulation layer only

222

223 **2.5 Carbon emission calculation**

224 As the global warming effect has posed serious threats to our climate, the environmental impact
225 especially the carbon emissions over the life cycle period should be considered and assessed
226 for the selected retrofit packages. The environmental impact associated with the generation of
227 the primary energy consumed (operation) and the utilization of renewable energies for
228 leveraging the carbon reduction are assessed. The primary energy consumption takes into
229 account of the overall primary energy requirement for heating, domestic hot water and
230 electricity consumption. Equivalent carbon emission factors are used to compare the emissions
231 from various greenhouse gases based upon their global warming potential (GWP) on a 100-
232 years' time frame.

233 The equivalent carbon emissions factors applied in this study are considered as follows:

234   • District heating: $0.22 kgCO_2eq/kWh$. As in Norway, the district heating system is
235   mainly powered by waste incineration [55].

236   • Electricity: $0.18 kgCO_2eq/kWh$, since the electricity is mainly generated by renewable
237   hydropower in Norway [56].

238   • Solar thermal system and solar PV: $0.051\ CO_2eqkg/kWh$ and $0.13 kgCO_{2eq}/kWh$
239   respectively [57].

240 The accumulated carbon cost of the measures/packages over the life cycle period equals to the
241 sum of the annual greenhouse gas emissions multiplied by the expected price per tones CO2
242 equivalent of greenhouse gas emission allowances in every year issued. Thus $C_{c,i}(j)$ can be
243 calculated using the following equation:

244 $$C_{c,i}(j) = \sum_{i=1}^{\tau}(C_i(j) * P_j) \qquad\qquad\qquad \text{Eq. (4)}$$

245 Where $C_i(j)$ is the annual greenhouse gas emission due to retrofit combination package j; P_j is
246 the expected price per tones CO_2 equivalent of greenhouse gas emission allowances in every
247 year issued. According to EU guideline [58], the momentary value of environmental damage
248 for polluting emissions, in terms of cost per tonne of CO_2 will be considered as €20 per tonne
249 of CO_2 equivalent until 2025, €35 until 2030 and €50 beyond 2030.

250 **3. Results and discussion**

251 **3.1 Primary energy consumption analysis**

252 Based on the simulations performed, the primary energy consumptions for the baseline building
253 and the selected 18 retrofit combination packages are shown in Table 6. Compared with the
254 primary energy consumption ($129.1 kWh/(m^2\ year)$) of the baseline model, some of the selected
255 combination packages could achieve very high energy consumption reduction, especially when
256 the retrofit level improved from Moderate Retrofit towards Extensive Retrofit. For instance,
257 about 55.6% of combination packages indicated primary energy consumption reaching less than
258 $95 kWh/(m^2\ year)$, which was at least approaching the EPC standard class B according the
259 Norwegian passive house standard [59]. The results of the simulation of Moderate Retrofit III
260 and Extensive Retrofit indicated more than 45% primary energy reductions as compared with
261 baseline condition. More detailed discussion will be presented combined with economic and
262 carbon emission reduction in the following section.

263

Table 6 Energy performances for the application of various retrofitting packages

Retrofit level	Combination packages	% reduction compared with baseline	Energy consumption for heating EP_h (kWh/m² year)	Energy consumption for domestic hot water EP_w (kWh/m² year)	Energy consumption for electricity EP_e (kWh/m² year)	Primary energy consumption EP(kWh/m² year)
	Baseline		**123.1**	**26.0**	**42.5**	**171.6**
Moderate Retrofit-I	COMB01	13.64%	79.6	26.0	42.6	148.2
	COMB02	14.80%	77.7	26.0	42.6	146.2
	COMB03	6.24%	92.4	26.0	42.6	160.9
	COMB04	17.25%	73.4	26.0	42.6	142.0
Moderate Retrofit-II	COMB05	22.26%	62.6	26.0	44.8	133.4
	COMB06	24.71%	73.0	26.0	30.2	129.2
	COMB07	40.21%	46.5	26.0	30.2	102.6
	COMB08	39.45%	33.1	26.0	44.8	103.9
Moderate Retrofit-III	COMB09	50.52%	25.2	3.7	56.0	84.9
	COMB10	34.27%	48.3	6.4	58.1	112.8
	COMB11	34.50%	46.1	6.3	60.0	112.4
	COMB12	43.71%	32.3	5.1	59.2	96.6
Extensive Retrofit	COMB13	50.82%	29.0	0	55.5	84.4
	COMB14	57.98%	29.0	0	43.2	72.1
	COMB15	57.23%	32.3	5.1	36.0	73.4
	COMB16	57.93%	12.5	2.5	57.2	72.2
	COMB17	71.45%	12.5	2.5	34.0	49.0
	COMB18	83.10%	0.3	0	28.8	29.0

265

266 **3.2 Cost-optimal and carbon emission analysis**

267 Although critically important, the primary energy consumption cannot be treated as the only

268 benchmark for the retrofit decision making process. As discussed in section 2, cost-optimal

269 method has been applied in this research, taking into considerations of the investment costs,

270 energy costs, maintenance costs, replacement costs and residual costs of the building

271 components for the proposed various retrofit combination packages. The detailed investment

272 costs for the selected 18 combination packages have been illustrated in Figure 4. It can be seen

273 that the investment costs of "Moderate Retrofit-I" (COMB01-04) are more or less the same as

274 in "Moderate Retrofit-III" (COMB09-12). The lowest investment costs are COMB 05 and
275 COMB06, which mainly include HR, SP, ED and AT. COMB 14-18 generally show the highest
276 investment costs, due to the high initial equipment costs for renewable EEMs.
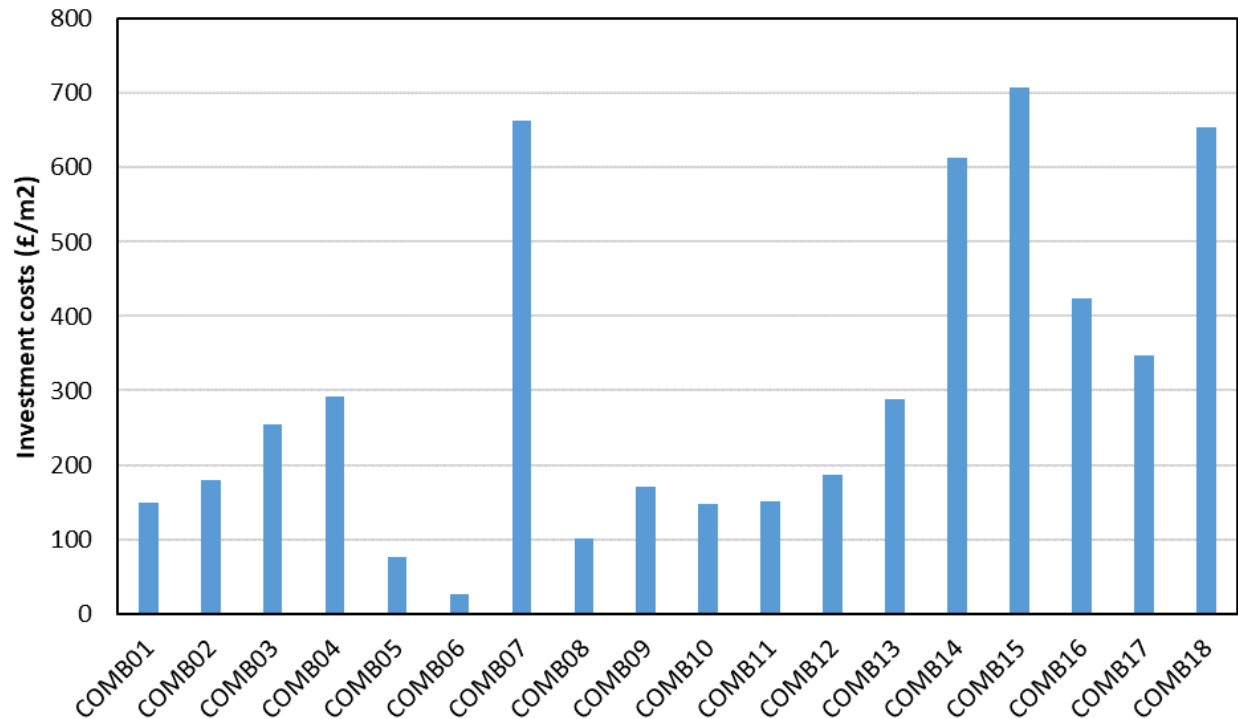

277

278   Figure 4 Investment costs for selected retrofitting combination packages

279 Applying the cost-optimal method, the detailed primary energy consumption, global costs,
280 payback period and carbon emissions for the 18 combination packages are presented in Table
281 7. The results were analysed and discussed in the following sections from the perspectives of
282 return of investment, environmental impacts and sensitivity of renewable products prices.

283

284 Table 7 Primary energy consumption, global costs, payback period and carbon emission for
285 various retrofitting combination packages

	Primary energy consumption EP(kWh/m² year)	% reduction compared with baseline	Global costs(€/m²)	Payback period	Equivalent CO2 emission (KgCO2/ m²)
Moderate Retrofit-I: only include passive measures					
COMB01	148.2	13.64%	270.2	42.7	30.9
COMB02	146.2	14.80%	274.4	46.6	30.5
COMB03	160.9	6.24%	306.4	142.3	33.7
COMB04	142.0	17.25%	300.5	86.9	29.5
Moderate Retrofit-II: include both passive measures and active measures					
COMB05	133.4	22.26%	211.9	18.0	27.6
COMB06	129.2	24.71%	216.4	5.4	27.2
COMB07	102.6	40.21%	350.8	69.4	21.4
COMB08	103.9	39.45%	208.0	13.3	21.1
Moderate Retrofit-III: include 1 renewable energy measure and other passive/active measures					
COMB09	84.9	50.52%	206.4	17.6	16.4
COMB10	112.8	34.27%	262.6	22.4	22.5
COMB11	112.4	34.50%	235.9	22.8	22.3
COMB12	96.6	43.71%	227.3	22.4	18.9
Extensive Retrofit: include 2 renewable energy measures and other passive/active measures					
COMB13	84.4	50.82%	244.9	29.6	17.7
COMB14	72.1	57.98%	306.4	44.8	19.3
COMB15	73.4	57.23%	312.0	44.6	21.9
COMB16	72.2	57.93%	274.0	38.2	13.6
COMB17	49.0	71.45%	189.0	21.6	16.6
COMB18	29.0	83.10%	278.5	38.0	10.4

286

3.2.1 Return of investment

287 Figure 5 illustrates that COMB 05 and 06 yield the lowest global costs (around 210 €/m²), but

288 the energy reduction compared with baseline case is only about 40kWh/m² year, which is

289 relatively high compared with other combination packages. By integrating 3-4 EEMs into the

290 combination packages, COMB 09-12 show the global costs to be in the range of 250-300€/m²,

291 which is about 1.2-1.4 times higher than COMB 05/06. The average energy reductions of

292 COMB09-12 are in the range of 84.9-112.8 kWh/ m² year, which is on average 35kWh/ m² year

293 less compared with COMB 05/06. COMB 13-16 respectively integrated 1 passive, 1 active and

294 at least 2 renewable energy measures together. The addition of more renewable energy

295 measures demonstrates significant primary energy reduction (up to 100kWh/ m² year compared

296 with baseline case). However, this has to be compensated by higher global costs. The global

297 costs for COMB13-16 are 300-450€/m², which are about 1.4-2.1 times higher than the lowest

298 value (COMB 05/06). Among all the Extensive Retrofits, COMB 17 offers the lowest global

costs (278.5€/m^2) with the primary energy reduction of 123 kWh/ m^2 year. COMB18 shows the highest final energy reduction (about 142kWh/ m^2 year) with relatively reasonable global costs (around 278.5€/m^2). It is possible to make different choices based on the available investment budget and the target primary energy reduction. If aiming for retrofitting with lowest investment costs, it would be practical to choose COMB 05/ 06. If the landlord is able to afford high investment costs with the aim to reduce the annual energy consumption, COMB 08, COMB9-12 could become attractive solutions.

Figure 5 illustrates that, in general, "Moderate Retrofit I" (COMB01-04) consumes more energy as compared with other combination packages. While the global costs for "Moderate Retrofit I" (COMB01-04) are within the medium level as compared with other 18 combination packages. This may be due to the fact that, the current baseline building has already been equipped with double-glazing and external insulation. Therefore, the further addition of insulation layers into the existing building fabric and the replacement of double-glazing with triple glazing makes very little difference to the primary energy consumption. It can be concluded that, for the specific baseline building, COMB01-04 would not be a cost-effective solution.
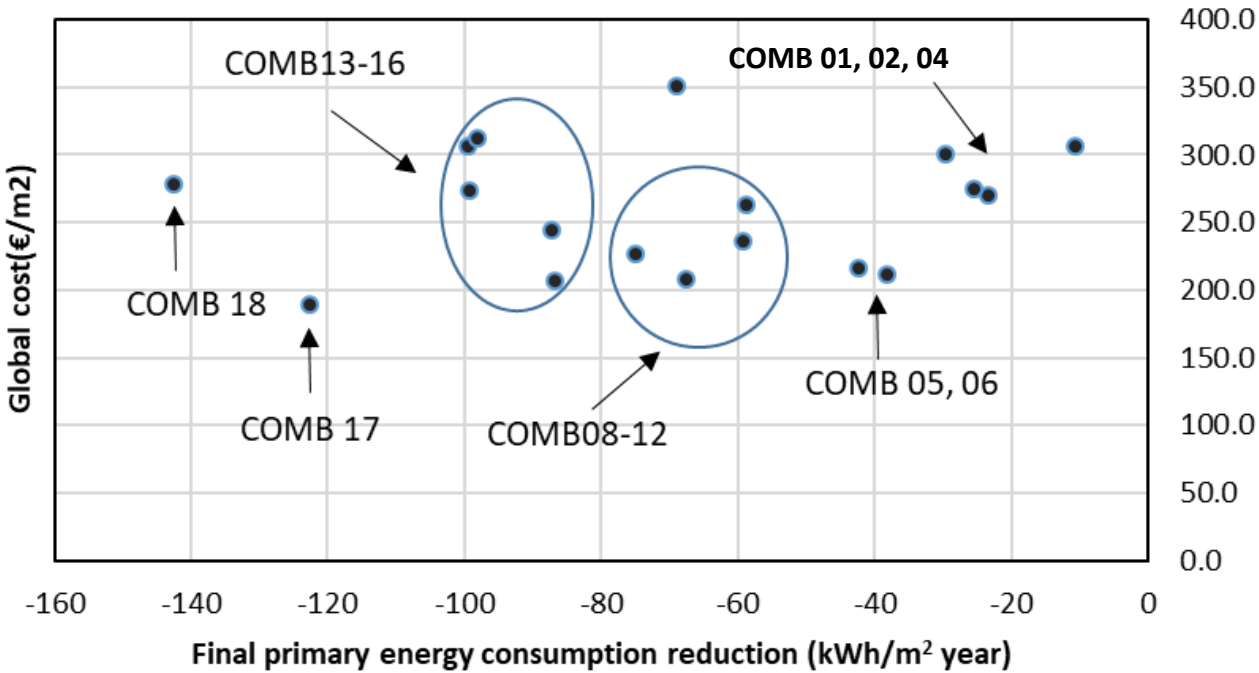

Figure 5 The variations of global costs with respect to final primary energy consumption reduction

Figure 6 illustrates the variations in payback periods with respect to primary energy consumption for the selected combination packages. With the integrations of passive and active EEMs, COMB05/06 demonstrate the lowest payback period, with the primary energy

consumption around 125kWh/m^2 year. COMB09-13 and COMB14-16 indicate similar payback periods. Since COMB14-16 includes an additional renewable EEM than COMB09-13, the primary energy consumption is about 27.8% less than the latter. COMB 17-18 have the lowest primary energy consumption which is less than 35 kWh/m^2 year than COMB 17-18, which have relatively high payback periods (approximately 20-40 years).

In order to make it possible to compare the energy level of the proposed COMBs with other houses, the energy performance certificate (EPC) standard has been applied. According to regulation document PRNS3700 and TEK2017 official standard [49] [60], the overall energy consumption should be less than 85 kWh/ m^2 year for class A, followed by 95kWh/m^2 year, 110 kWh/ m^2 year, 135 kWh/ m^2 year and 160 kWh/ m^2 year respectively for class B-E. The detailed EPC classification has been included in Figure 6. It is obvious that the EPC level of "Moderate Retrofit I" (COMB01-04) fall above class D and E, which do not satisfy the Norwegian Passive House standard [49] with less than 120 kWh/ m^2 year annual primary energy consumptions. Therefore, Moderate Retrofit I should be phased out.
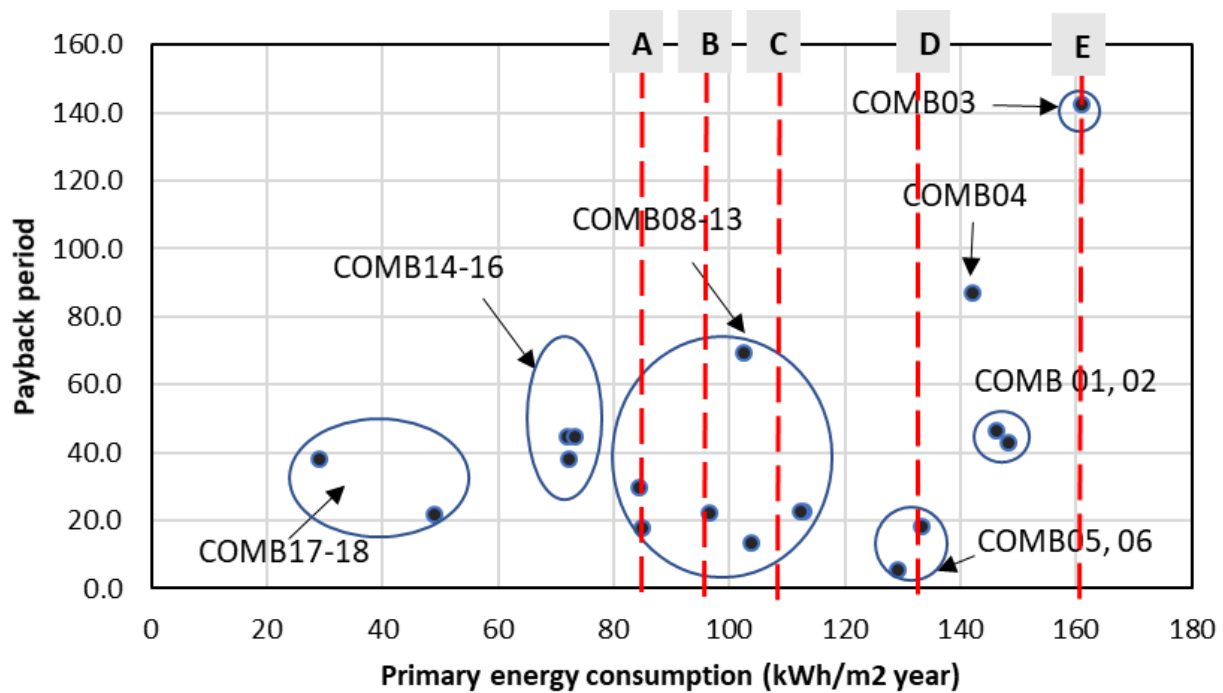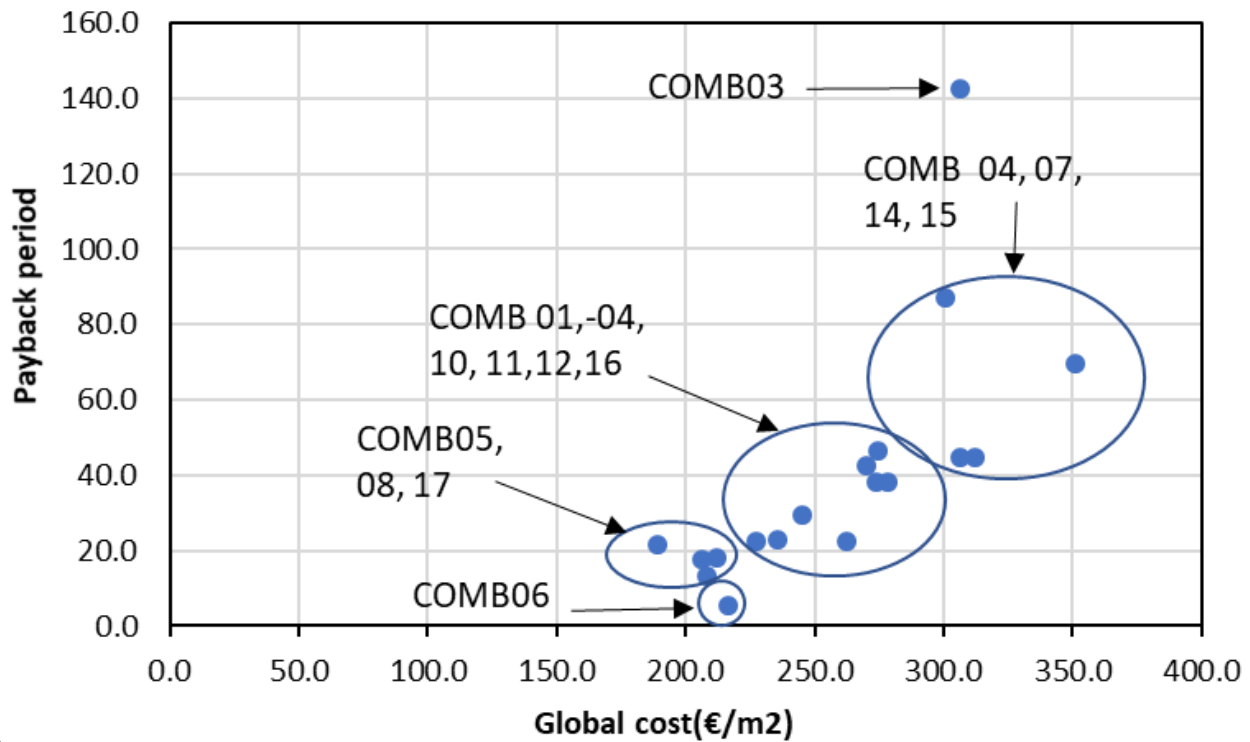

Figure 6 Variations of payback periods with respect to primary energy consumptions

After eliminating COMB01-04, the remaining combination packages were evaluated based on the relationship between payback period and global costs and the results are shown in Figure 7. It can be seen that COMB05, 06, 08 and 17 represent the shortest payback period (below 20 years) with the global costs less than 220 €/m^2. COMB10, 11, 12, 16 also yield relatively short payback period (about 25-30 years). By integrating 3-4 EEMs together, COMB04, 07, 14, 15

343 demonstrates relatively high initial investment costs, which lead to increased global costs (300-
344 350 kWh/m^2 year).

3.5

346 Figure 7 Variations of payback period with respect to global costs

347 **3.2.2 Environmental impact**

348 Figure 8 illustrates the variations of equivalent CO2 emissions with respect to primary energy
349 consumptions, in combination with EPC standard classifications. Using the threshold of 130
350 kWh/m^2 year from Passive House standard, COMB01-05 should be phased out due to the high
351 primary energy consumption. COMB 07, 08, 10-12 could be classified under EPC standard
352 category C and D, with the equivalent carbon emission between 15-25kgCO$_2$/m^2. Even though
353 there are similar primary energy consumption levels COMB14-16 show diversified equivalent
354 carbon emissions, in the range of 15-25kgCO$_2$/m^2. This is due to the fact that carbon emission
355 factor varies significantly for different renewable energy sources (0.051 CO$_2$ kg/kWh for solar
356 thermal and 0.13kgCO$_2$/kWh for solar PV), which leads to different equivalent carbon
357 emissions. Integrating all the EEMs, COMB18 leads to the lowest primary energy consumption
358 and equivalent carbon emission. Further observation of Figure 8 indicates that COMB 09 and
359 13 demonstrate approximately the same level of primary energy consumption and equivalent
360 carbon emission. It would therefore be interesting to further analyse these two combination
361 packages based on the global costs and payback period, as shown in Figure 8 and Figure 9.
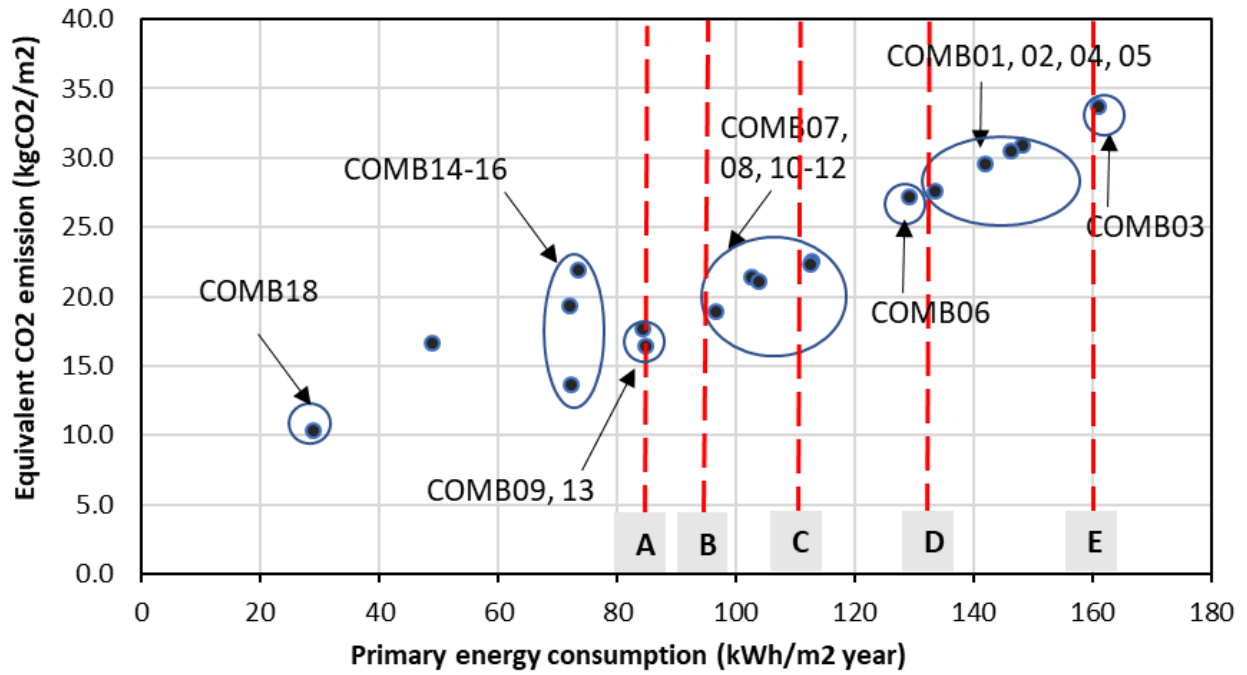
362

Figure 8 Variations of equivalent CO2 emissions with respect to primary energy
364 consumptions

365 Figure 9 illustrates the variations of equivalent CO_2 emissions with respect to global costs for

366 various combination packages. It could be noted that COMB17 yields the lowest global costs

367 ($189.0€/m^2$) with equivalent CO_2 emission equals to $16.6kgCO_2/m^2$, followed by COMB05

368 ($211.9 €/m^2$) with equivalent CO_2 emission of $27.6 kgCO_2/m^2$. With 3-4 EEMs included,

369 COMB14 and 15 show global costs around $300€/m^2$, which is about 1.4 times higher than

370 COMB 08-13. The average equivalent CO_2 emission is in the range of $16.4-22.3 kWh/m^2$ year,

371 which are in the same level as COMB08-13. COMB18 indicates the lowest equivalent CO_2

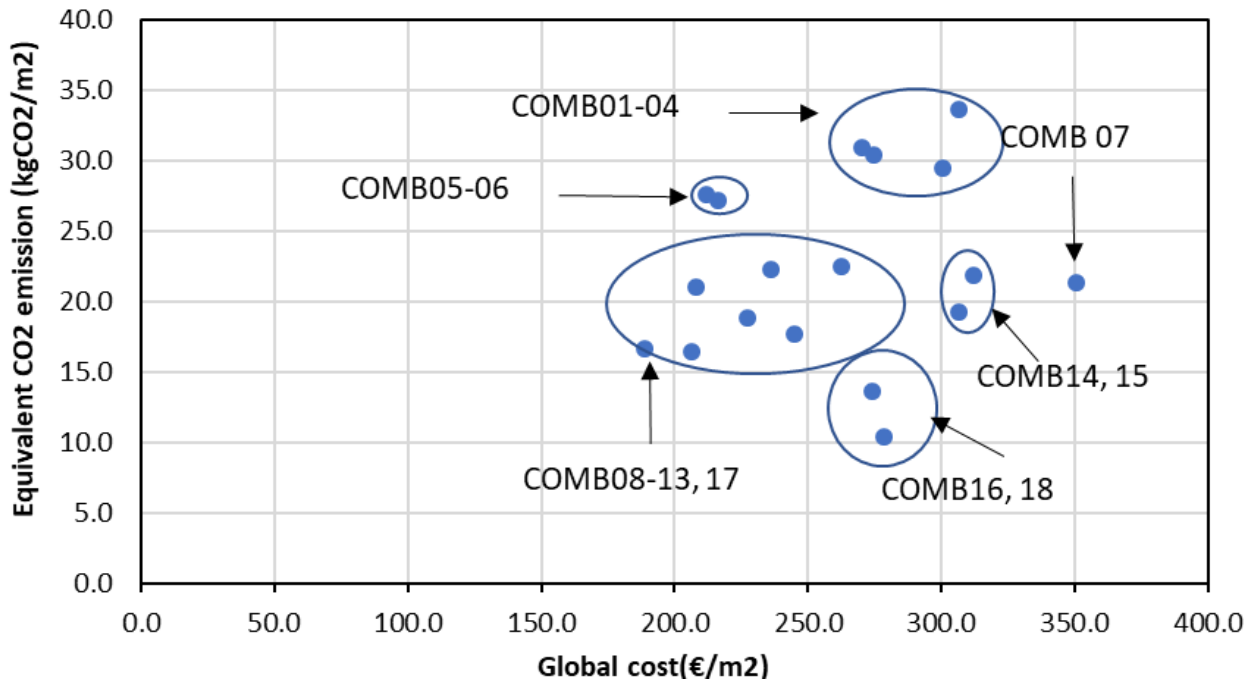372 emission with the global costs of $278.4 €/m^2$.

Figure 9 Variations of equivalent CO_2 emissions with respect to global costs
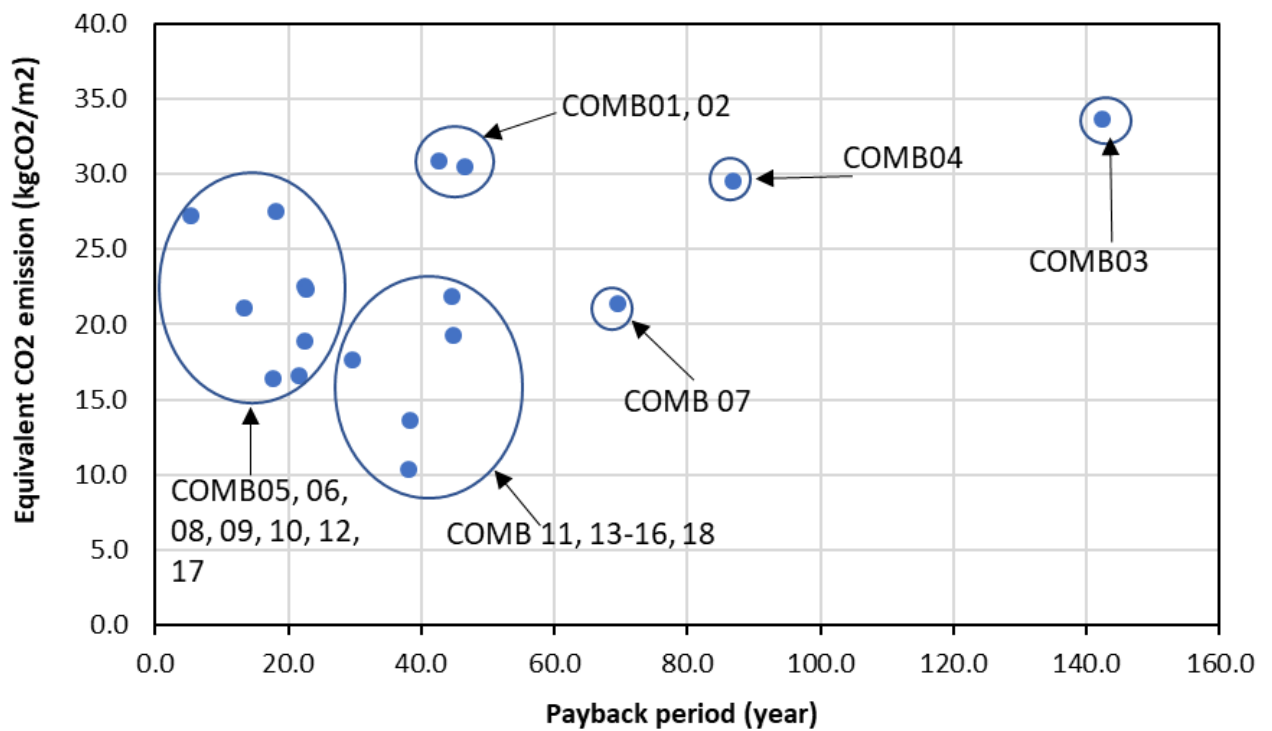

Figure 10 Variations of equivalent CO_2 emissions with respect to payback periods

Figure 10 shows the variations of equivalent CO_2 emission with respect to payback period for the 18 COMBs. It can be found that in general, COMB 05, 06, 08-12 and 17 represent the shortest payback period (less than 20 years) with equivalent CO_2 emission averagely equals to $22kgCO_2/m^2$. Two groups of combination packages, including COMB11 and 13-16, 18 demonstrate the similar level of equivalent CO_2 emission (10.2-22.8 $kgCO_2/m^2$), and the

382 payback period varies averagely from 30 to 40 years. It could be noted that although COMB13-

383 18 are all within Extensive Retrofit, COMB17 actually yields relatively shorter payback period

384 (21.6 year) compared with COMB13-16,18 (38.0-44.8 years). The reason may be that

385 COMB17 only incorporates 2 renewable EEMs with fully equipped BIPV, which generates

386 significant amount of electricity, contributing greatly to the reduction of annual energy

387 consumption.

388 **3.3 Sensitivity of renewable energy product prices**

389 Critical parameters including the market discount rate and interest rates are proven to have great

390 impacts on the cost optimal analysis [17, 18, 61]. These parameters are affected drastically by

391 the national economic development and the technology advancements over the years.

392 Additionally, according to the EU renewable energy directive 2009[62], the EU is aiming at

393 20% less energy consumption with the utilization of renewable energy sources. In meeting this

394 target, countries within EU have introduced various national incentives to facilitate the

395 implementation of renewable energy [63]. Moreover, through technology development and

396 advanced manufacturing techniques upgrading, the investment costs of renewable energy could

397 be greatly reduced. However, the drop in renewable energy investment costs have not been

398 considered in other research studies. This study shows that the sensitivity of renewable energy

399 price has been moderately reduced by 3%, 5% and 7% respectively. Considering the

400 government incentives to encourage the small-scale on-site electricity production, the PV

401 generated electricity feed-tariff rate is also considered to be increased by 3%, 5% and 7%

402 respectively in the future. Extensive Retrofit packages COMB14, 15, 17 and 18, which include

403 a number of renewable EEMs (solar PV, BIPV) have been selected to conduct such sensitivity
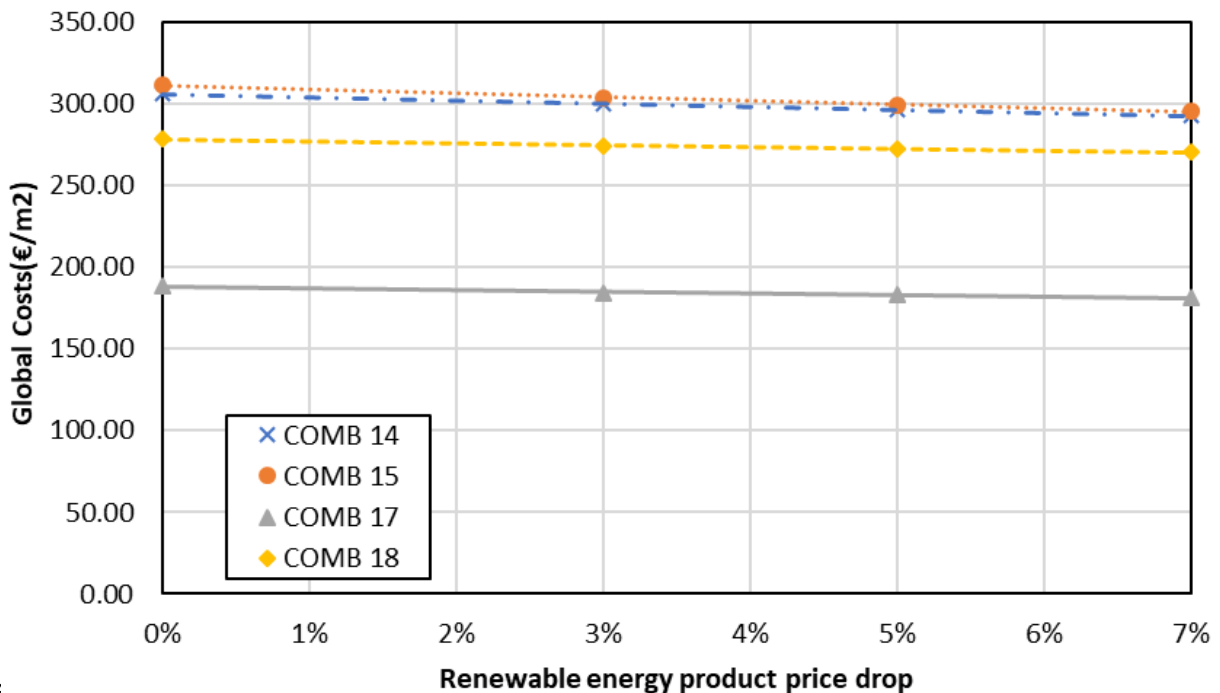
404 analysis.

405 The investment costs, global costs and payback period for COMB 14, 15, 17 and 18 with respect

406 to the decreasing renewable energy product price from 3% to 7% are illustrated respectively in

407 Figure 11-13. It can be seen that the reductions for investment costs, global costs and payback

408 periods are in the range of 1.4% to 6.2%, 1.5% to 2.7% and 1.9% to 7.2% respectively as the

409 renewable energy product price reduces from 3% to 7%. Among the four selected combination

410 packages, COMB 15 is more sensitive to the changing price of renewable energy product, with

411 the maximum 7.2% payback reduction. COMB 17 is ranked as the 2nd most sensitive to the

412 changing renewable energy product price, while COMB 14 and COMB 18 are less sensitive.

413 The reason is that COMB 15 and 17consider the full usage of the roof space for the installation

414 of BIPV, with total area of 384m². While the total installed BIPV area in COMB 14 and 18 are

415 only 240m². The amount of electricity generated by BIPV are higher in COMB 15/17 than that

416 in COMB14/18, which leads to greater changes in cost optimal analysis under the reduced

417　renewable energy price. Further inspection of Figure 11-13 reveals that, although the
418　investment cost for COMB 15 is about 13.1% higher than COMB 14, due to the contributions
419　of extra BIPV installed, the global costs and payback periods for COMB 14 and 15 are about
420　the same despite the drop in renewable energy product price. Hence, it could be concluded that
421　in the future with favourable government incentives for renewable energy, it is more cost
422　effective to install renewable energy systems to their full capacity in building retrofit projects.
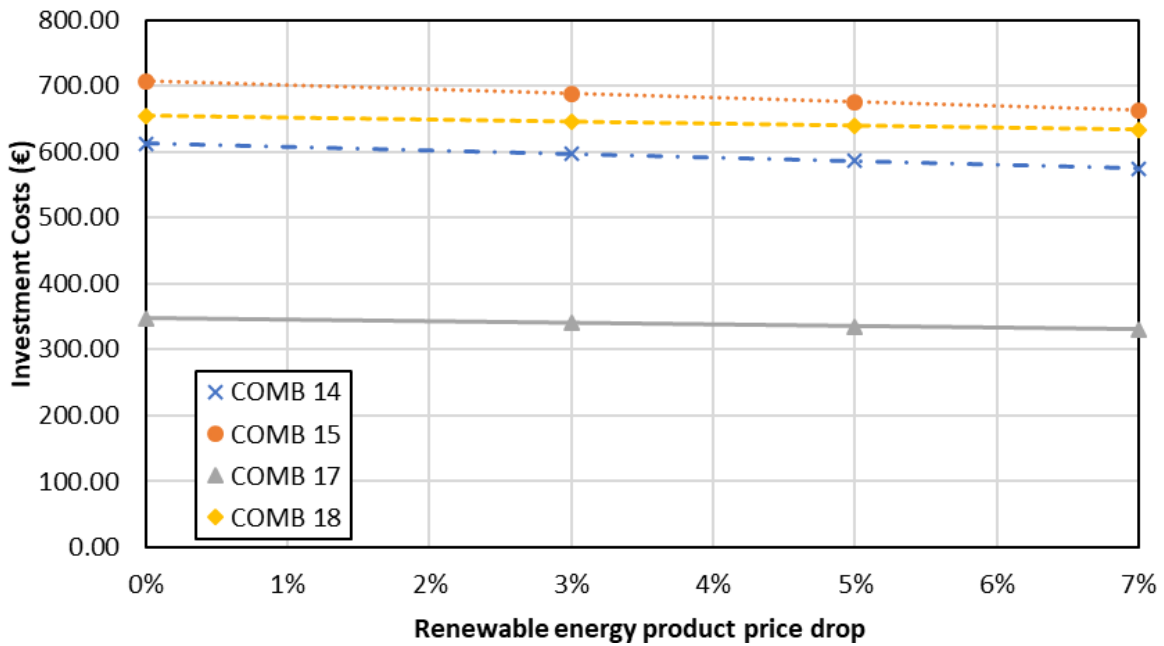
423

424　Figure 11 Variations of investment costs with respect to the renewable energy product price
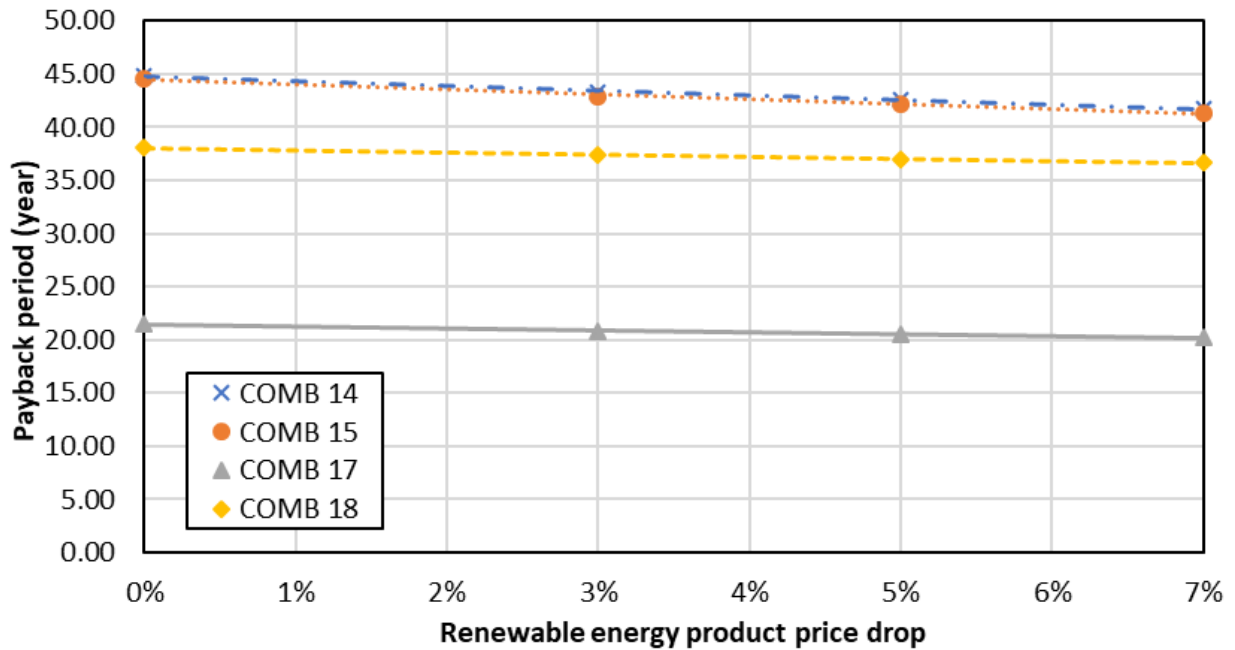425　drop (PV generated feed in tariff rate increased by 7%)

426

30

429

430 Figure 13 Variations of payback period with respect to renewable energy product price drop
431 (PV generated feed in tariff rate increased by 7%)

432 Table 8 indicates the influence of increasing the PV generated feed in tariff rate on the

433 investment cost, global cost and payback period for the selected COMBs. By increasing the

434 PV generated feed in tariff rates from 3% to 7%, the global cost and payback period is

435 reduced by 0.2% -2.2% and 0.2%-1.1% respectively. Changes in PV generated feed in tariff

436 rate will have no effect on the investment cost, due to the reason that such incentives will only

437 be related to the annual energy utilization.

438 Table 8 Variations of increasing PV generated feed in tariff rate on the investment cost,
439 global cost and payback period for selected combination packages

COMBs	Increase of PV generated feed in tariff rate	0%	3%	5%	7%
COMB14	Investment cost (€)	612.7	612.7	612.7	612.7
	Global cost (€/m^2)	306.35	305.90	305.59	305.28
	Payback period (year)	44.80	44.67	44.59	44.51
COMB15	Investment cost (€)	706.8	706.8	706.8	706.8
	Global cost (€/m^2)	312.00	305.90	305.59	305.28
	Payback period (year)	44.59	44.67	44.59	44.51
COMB17	Investment cost (€)	347.7	347.7	347.7	347.7
	Global cost (€/m^2)	189.00	188.14	187.56	186.98
	Payback period (year)	21.56	21.46	21.39	21.33
COMB18	Investment cost (€)	654.1	654.1	654.1	654.1

		278.53	278.07	277.76	277.46
Global cost (€/m²)		278.53	278.07	277.76	277.46
Payback period (year)		38.04	37.95	37.90	37.84

440

3.4 Multi-criteria assessment approach

3.4.1 Social analysis of the retrofit combination packages

Apart from the energy saving, carbon emission and cost-optimal analysis performed in the previous sections, the social impacts (including "disturbance to occupants", "indoor air quality and comfort" and "building aesthetics") for the defined retrofit combination packages are also assessed based on the pre-retrofit occupancy survey. Table 8 summarizes the energy, economic, environmental and social factors for the selected 18 COMBs. In Table 8, the numerical ranking "9" stands for the most favourable and beneficial combination condition, while ranking "1" represents the most disadvantageous solution.

"Disturbance to occupants" is generally related to the EEMs that are going to involve substantial amount of construction works, which will bring various kinds of disturbances (noise, road closure, temporary power shutdown and even temporary evacuation from the flats/rooms) to the occupants during retrofit process. For the proposed COMBs in this research, such disturbances will mainly be expected from WI, BIPV and GSHP. The insulation installation (WI) will involve the temporarily evacuation of the residents from the apartments. The installation of GSHP will involve the excavation and installation of vertical boreholes/loops in close proximity to the demo site building. Therefore, in Table 8, the social ranking for COMB 02, 03, 04, 07, 09-18 are relatively low.

"Indoor air quality and comfort" concerns have been raised by the occupants in the pre-retrofit questionnaires. About 66.3% of residents complain about the overheating problems during the winter heating season, which could be solved by installations of SP. The moisture and condensation in the kitchen and toilet space are also reported by the occupants, who are suffering from unpleasant indoor odours without proper ventilation system. Therefore, the COMBs including HR could help to improve the indoor air quality and recover the waste heat effectively. Hence, in Table 8, the social benefits for COMB 06-08, 16-18 are relatively higher due to the upgrading with SP and HR.

"Building aesthetics" is related to the EEMs that are causing changes to the existing building façade and surrounding areas. For instance, the installations of external wall insulation (WI) and BIPV/ST on the roof is posing major changes to the existing building facades. Additionally, according to the Oslo city planning regulations, retrofit interventions which cause major

471   changes to building façade will need to be approved under special licences. Therefore, in Table

472   8, the COMBs (02-04, 13-18) including WI, BIPV and ST will have low social ranking.

473   **3.4.2 Multi-criteria assessment taking into account of various stakeholders' preferences**

474   Retrofit projects involve various stakeholders (occupants, landlords, local planning authority,

475   policy makers) who play important roles during the retrofit decision making process. Using the

476   RezBuild project as an example, the three demo site project leaders (OBOS Ltd.- Norway,

477   Comunidad de Madrid- Spain and Officinae Verdi Spa-Italy) work closely with the occupants

478   to collect pre-retrofit survey results, with the aim to understand the occupants' demands and

479   concerns (indoor air quality and comforts, less disturbance during retrofit construction process,

480   reduced annual energy bills) during the retrofit process. The demo site leaders actually act as

481   the project coordinators who also liaise with the local governments for obtaining additional

482   building planning permissions. During this process, the local government will express their

483   attitudes specially related to the construction plan, maintaining historical aesthetics of the

484   building and reducing the disturbance to local communities. The policy makers at the national

485   government level will specifically focus on the impacts of energy saving/carbon reduction

486   potentials and renewable EEMs implemented, which can serve as important guidance for other

487   similar building retrofit projects. The landlords will take part in the decision making process,

488   with special emphasis on the changes to the building layouts/structures, long term energy saving

489   and associated costs/payback period.

490   In order to capture various stakeholders' preferences for the proposed retrofit EEMs and

491   combination packages, the "lessons learned" online survey covering a wide range of questions

492   from multi-criteria perspectives (energy, economic, environmental and social) was designed

493   and distributed within RezBuild project partners and their clients, who represent a wide range

494   of stakeholders (occupants, landlords, local government, designer, project manager, etc). Based

495   on the collected 38 copies of survey, the weighting factors (in the range of 0-1) representing

496   various stakeholders' preferences are summarized in Table 10. Higher weighting factor value

497   means that the stakeholders express special attentions in this respect.

498   Finally, with the aim to provide numerical ranking for the proposed COMBs from multi-criteria

499   and in the meantime reflecting various stakeholders' perspective, the energy, economic,

500   environmental and social ranking factor (EEES) has been defined as the sum of the

501   multiplications between the various multi-criteria factors and the relevant weighting factors.

502   EEES can be calculated using following equation):

503    $EEES_i = \sum(MC_j \times W_k)$ Eq. (5)

504 Where MC_j represents the multi-criteria factors, which can be obtained from Table 9. W_k is the
505 weighting factors shown in Table 10. The subscript "i" indicates the various stakeholders'
506 pespectives. For instance, the EEES ranking value for occupants' perspective on COMB01
507 could be calculated as: 2*0.8+7*0.2+3*0.2+4*0.4+9*0.8+5*0.8+9*0.5=20.9. In this way, the
508 proposed 18 COMBs have been ranked using EEES factor and illustrated in Figure 14. It is
509 obvious that COMB 05, 06 are ranked as the most favourable solutions for 3 typical
510 stakeholders (occupants, landlords and local government). This is followed by "Moderate
511 Retrofit-III" (COMB 09-12), with EEES ranking averagely 13.2% less than COMB05/06. The
512 3rd highest EEES ranking is "Extensive Retrofit", which involves more renewable EEMS.
513 COMB 03/04 are ranked as the most unfavourable ones, which agrees well with the
514 aforementioned results obtained using Norwegian Passive house EPC grade. Using this multi-
515 criteria assessment approach, the various stakeholders' preferences could be numerically
516 quantified from energy, environmental, economic and social perspectives. This multi-criteria
517 assessment approach provides an easy and user-accessible tool which significantly facilitates
518 the retrofit decision-making process with wider stakeholders' engagement.

519 Table 9 Multi-criteria factors for various COMBs from energy, economic, environmental and
520 social aspects

Retrofit Level	Combination Package (COMB)	Energy factor	Economic factor		Environmental factor	Social factor		
		Primary Energy Reduction	Global Costs	Payback Period	Carbon Emission Reduction	Disturbance to Occupants	Indoor Air Quality and Comfort	Building Aesthetics
Moderate Retrofit-I	COMB01	2	7	3	4	9	5	9
	COMB02	2	7	3	3	3	5	6
	COMB03	2	3	1	3	3	4	6
	COMB04	2	3	2	4	3	6	6
Moderate Retrofit-II	COMB05	3	9	8	5	9	7	9
	COMB06	3	9	9	5	9	8	9
	COMB07	4	2	2	6	2	8	6
	COMB08	4	9	8	6	8	9	6
Moderate Retrofit-III	COMB09	6	9	7	7	6	6	6
	COMB10	4	4	6	6	7	6	8
	COMB11	4	7	6	6	6	5	8

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|								
	COMB12	5	7	6	8	5	7	8
	COMB13	6	6	5	8	4	7	5
	COMB14	7	3	3	8	3	7	3
Extensive Retrofit	COMB15	7	3	3	6	4	7	3
	COMB16	7	7	4	8	2	9	4
	COMB17	8	9	6	7	2	9	5
	COMB18	9	4	4	9	1	9	3

521

522   Table 10 Weighting factors representing various stakeholders' preferences

Weighting factor		Occupants	Landlords	Local government
Energy	Primary Energy Reduction	0.8	0.6	0.6
Economic	Global Costs	0.2	0.8	0.6
	Payback Period	0.2	0.8	0.6
Environmental	Carbon Emission Reduction	0.4	0.4	0.8
Social	Disturbance to Occupants	0.8	0.5	0.8
	Indoor Air Quality and Comfort	0.8	0.6	0.6
	Building Aesthetics	0.5	0.8	0.8

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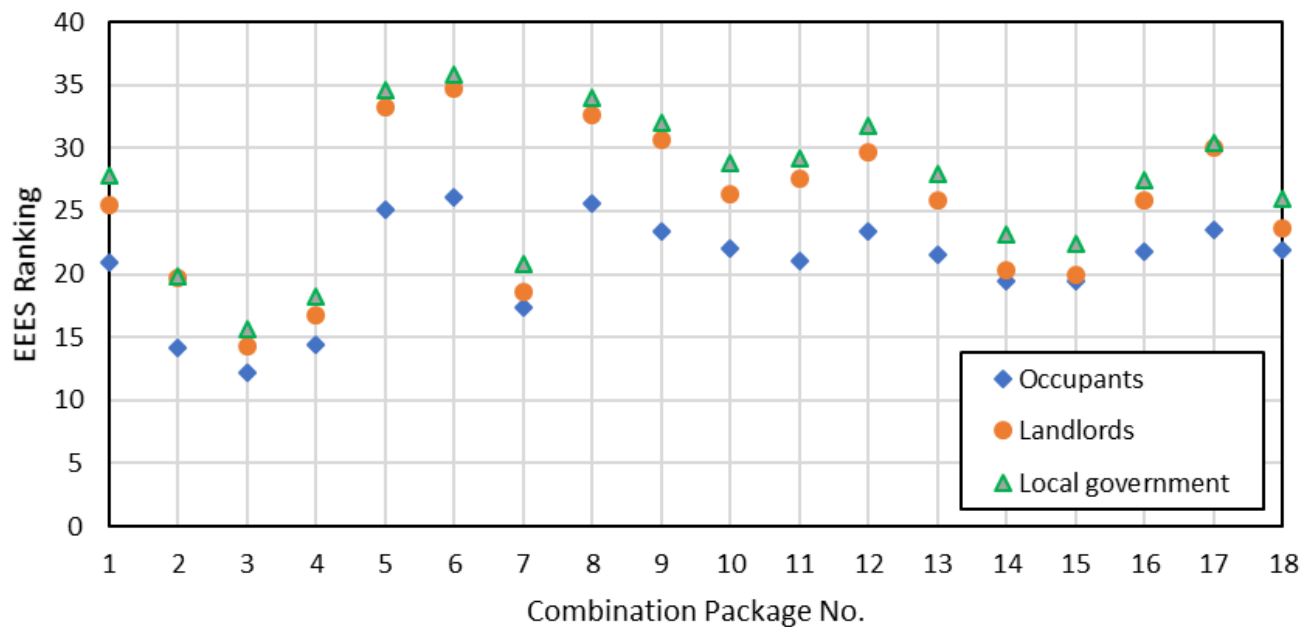
526   Figure 14 EEES rankings for the proposed combination packages from different
527   stakeholders' perspectives

528

529   **4. Conclusions**

530   This paper presents a multi-criteria assessment approach for a wide range of energy efficient
531   measure combinations applied for a residential building retrofit constructed in 1990s in
532   Norway. A number of energy efficient measures (EEMs) have been selected and identified into
533   three types (passive, active and renewable EEMs). Base on the level of energy saving potentials,
534   these EEMs have been combined into 18 retrofit combination packages and grouped into
535   various retrofit levels (Moderate Retrofit-I, II, III and Extensive Retrofit). The annual primary
536   energy consumptions (heating, hot water and electricity) for the selected combination packages
537   are simulated in IESVE software. A multi-criteria assessment approach featuring two levels of
538   assessments: i) combined energy, economic and environmental assessments; ii) social
539   assessment from various stakeholders' perspective was then adopted. This approach not only
540   presents a comprehensive overview for the selected combinations packages taking into account
541   of energy, economic and environmental saving potentials, but also   quantifies different
542   stakeholders' perspectives on the proposed combination packages, which enables wider
543   engagement from various stakeholders in the retrofit decision making process. The following
544   conclusions could be drawn from this research, which are valid for similar apartment building
545   blocks insulated according to the standard of 1990's and typically in the countries situated in
546   the cold climate zones.

547   At the first level, the comprehensive assessments of the proposed combination packages on the
548   primary energy consumption, global costs and carbon reduction were conducted. It can be
549   concluded that i) Increasing the numbers of EEMs in COMBs does not necessarily leads to
550   better building performance from energy, economic and environmental point of view.
551   "Moderate Retrofit II", which mostly includes 1 passive measure with 1-3 active measures,
552   demonstrates the lowest global costs and payback period, with primary energy reduction and
553   carbon emission ranked 4th among all the retrofit COMBs. ii) "Moderate Retrofit III" ranks
554   2nd and 3rd from economical and energy/environmental points of view. This group of COMBs
555   can be selected if the investment budget is not high enough to afford "Extensive Retrofit"
556   COMBs, while the requirements of carbon reduction are still demanding. iii) "Extensive
557   Retrofit" generally lead to lowest energy consumption and lowest equivalent carbon emission,
558   with highest percentage of energy reduction compared with baseline building scenario.
559   However, these COMBs are not economically feasible, due to the long payback period and
560   great amount of global costs.

561   At the second level, the social assessment survey was conducted with the aim to generate a
562   matrix of weighting factors in order to represent various stakeholders' views on the selected
563   COMBs. The energy, economic, environmental and social ranking factor (EEES) is calculated
564   as the sum of the total multiplications between the various factors and the relevant weighting

factors. Using such multi-criteria assessment approach, COMB05 & 06 (within "Moderate Retrofit-II") have been ranked and chosen as the most favourable retrofit solutions, with EEES value equals to 25.6 from typical stakeholders perspectives.

Due to the development of advanced materials and manufacturing process, the investment costs for renewable EEMs could be substantially reduced in the long term. The impacts of changing renewable energy prices and PV generated feed in tariff rates on the global costs, carbon reductions and primary energy consumptions, which have rarely been analysed in literature, are numerically investigated in this research. For "Extensive Retrofit", 3% to 7% reduction of prices for renewable energy products will lead up to 6.2%, 2.7% and 7.2% reductions respectively in investment costs, global costs and payback periods. It is more cost effective to equip the renewable energy measures to their full capacity, which offers lower global costs and shorter payback period.

With no dependences on fossil fuels and therefore environmental friendly features, the implementations of renewable energy are greatly recommended by the European Commission with further supports from national level government renewable incentives. Thus, in the future, the "Extensive Retrofit" proposed in this research, could lead to higher level of primary energy reduction and carbon footprint reduction. Additionally, the cost optimal analysis performed in this research has only considered the Norwegian government feed-in tariff incentives for solar PV. The other two renewable EEMs including ST and GSHP, are expected to receive more financial supports within EU, leading to dramatic market penetration and price reduction. Therefore, in the long term, Extensive Retrofits could become more affordable and cost effective.

Acknowledgement

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