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A Novel Holistic EPC Related Retrofit Approach for Residential Apartment Building Renovation in Norway

Abstract

This paper presents a novel Energy Performance Certification (EPC) related holistic building retrofit approach for a Norwegian apartment block built in 1980s. Based on the pre-combination principles of “Fabric priority”, “Renewable in supplement”, “Avoid complicated installation”, 11 energy retrofit measures (ERMs) were defined and combined into 18 typical retrofit combination packages (COMBs). Targeted simulations with the aim to explore the interconnected and coupled impacts of selected ERMs are performed in a dynamic simulation tool IES Virtual Environment (VE). A novel Energy Limiting Difference (ELD) assessment factor has been defined, which only considers the difference between primary and renewable energy consumption in the extreme cold winter and hot summer months. The post retrofit EPC standard for each COMBs are then linked with these ELD assessment factors respectively. The relationship between ELD assessment factors and the relevant EPC grades for the 18 COMBs is plotted and verified against the obtained EPC results. Without performing the simulation for each month in conventional retrofit approaches, this approach leads to at least 78% reduced simulation efforts. This ELD-EPC related approach could therefore be used as useful guidelines for similar apartment building retrofits incorporating renewable energy measures in high-density areas in the cold climate region.

Keywords: apartment building retrofit; energy retrofit measures; combination packages; building energy simulation; renewable energy

Abbreviation and acronyms

ACH	Hourly Air Change Rate
AI	Attic floor Insulation
BIPV	Building Integrated Photovoltaic
COMB	Combination Package
COP	Coefficient of Performance
DHW	Domestic Hot Water

ED	Efficient Lighting device
EPBD	Energy Performance of Building Directive
ERM	Energy Retrofit Measures
EPC	Energy Performance Certification
ELD	Energy Limiting Difference
EER	Energy Efficient Rate
GR	Triple Glazing Retrofit
GI	Garage Ceiling Insulation
GSHP	Ground Source Heat Pump
HVAC	Heating, Ventilation and Air Conditioning
HR	Heat Recovery
IES VE	Integrated Energy Simulation and Virtual Environment
LED	Light-emitting diode
PE	Primary Energy
RE	Renewable Energy
SP	Temperature Set Point Sensor
ST	Flat Solar Thermal Collector

1. Introduction

The global average surface temperature has risen about 1.1°C since the late 19th century, a change driven largely by the increased carbon dioxide and other human-related emissions into the atmosphere ("Global Climate Change Indicators," 2016). The European Commission has set up climate strategies with the aim to reduce greenhouse gas emissions by 40% and 80% respectively towards 2030 and 2050 in comparison to 1990 levels (EUROPEAN COMMISSION, 2011). The increasingly serious energy crisis and the demand for improving building indoor environmental quality and comfort levels have triggered great incentives for accelerating the development of energy efficient and innovative building technologies in the built environment sector.

Buildings are long-term assets which can have a life span of more than 50 years and 75-90% of those standing today are expected to remain in use in 2050 (EUROPEAN COMMISSION, 2016). However, in Europe, the building retrofits are carried out at low demolition rates (0.1% per year) and low retrofit rates (1.2% per year) (EUROPEAN COMMISSION, 2010). Most of the existing buildings in Europe are not energy efficient (Ma, Cooper, Daly, & Ledo, 2012; Rabani, Madessa, & Nord, 2017; Webb, 2017). According to Broin et al. (Ó Broin, Mata,

Göransson, & Johnsson, 2013; Project, January 2013), buildings in Europe consume about 40% of the total European energy usage and contribute to almost 36% of greenhouse gases. In order to comply with the Kyoto Protocol goals and help to decarbonize the European economy, the Energy Performance of Building Directive (EPBD) was established in 2002 (EUROPEAN COMMISSION, 2002) and updated in 2010 (EUROPEAN COMMISSION, 2010), setting strict targets to building sector with the estimated 40% greenhouse gases reduction by 2030. In order to achieve such energy target, the EU needs to boost the number of deep retrofits and to speed up the retrofit rate of the existing stock to above 2% annually (EUROPEAN COMMISSION, 2010). Within this context, many retrofit measures have been made to existing buildings with the aim to reduce energy consumption (Chen, Yang, & Sun, 2016; Paiho, Seppä, & Jimenez, 2015; Tadeu, Rodrigues, Tadeu, Freire, & Simões, 2015), improve indoor thermal comfort and air quality (Psomas, Heiselberg, Duer, & Bjørn, 2016) and move towards Low or Zero Energy Buildings (Desideri et al., 2013; Kylili & Fokaides, 2015). Comprehensive reviews on building retrofit have been presented by Ma et al. (Ma et al., 2012), Mazzarella (Mazzarella, 2015) and Serrano-Jimenez et al. (Serrano-Jimenez, Barrios-Padura, & Molina-Huelva, 2017).

Table 1 summarises the previous studies on various ERMs and their energy saving potential, with all the ERMs classified into passive, active and renewable measures. It can be noted that the corresponding energy saving potentials depend on the retrofit level and the numbers and features of ERMs included. The following conclusions can be drawn from Table 1:

- i) When only considering passive measures, 11%-45% of primary energy consumption can be reached, with glazing and air-tightness being the two crucial energy saving ERMs. The influence of wall insulation on the overall energy saving performance vary largely in different countries, due to differences in weather conditions and existing building conditions.

ii) The combination of passive and active measures can achieve around 34% to 51% of overall energy consumption reduction. The most energy efficient passive measures are replacing the existing lights with LED lighting technologies, the upgrading of heat recovery system and the installation of room temperature sensors and controllers.

iii) The combination of renewable energy with passive and active measures can achieve primary energy consumption reduction in the range of 71%-89% (close to near zero energy buildings' standards), which meets the deep retrofit goals.

Since the building fabric related passive retrofit measures have been chosen as the most easily applied ERM in published literature, we summarize it as the 1st principle of “Fabric Priority” when choosing the energy retrofit measures (ERMs). From the simulation procedure point of view, renewable energy measures can serve as a supplement to “Fabric Priority” and further reduce the building primary energy load. This can be concluded as the 2nd principle of “Renewable in supplement”. Moreover, according to previous literature and surveys (Balcombe, Rigby, & Azapagic, 2013; Baumhof, Decker, Röder, & Menrad, 2018; Martek et al., 2019; Menassa & Baer, 2014; Mills & Rosenfeld, 1996), it should be noted that some complicated retrofit ERMs (e.g., external wall insulation, pipe and roof replacement) would cause serious disturbance to residents live nearby. Therefore, the 3rd principle of “Avoid complicated installation process” needs to be considered to save time and cost for the retrofit process.

Reference	Building type	Location, construction year	Passive Measures				Active Measures				Renewable Measures			Pre-retrofit baseline energy consumption	Post-retrofit energy consumption	Conclusions
			EWI	RI	GR	AT	ED	TSCV	MVHR	EE	PV	SC	HP			
Casquero-Modrego et al. (Casquero-Modrego & Goñi-Modrego, 2018)	Apartment building	Spain, 1964	✓	✓	N/A	N/A	N/A				N/A			37 kWh/m ² thermal energy consumption in winter	33 kWh/m ² thermal energy consumption in winter (11% reduction)	Envelope retrofit can improve the thermal comfort and the energy savings.
Fan et al. (Fan & Xia, 2018)	Office building	South Africa, N/A	✓	✓	✓	N/A	✓	N/A	N/A	N/A	✓	N/A	✓	EPC grade E	EPC grade A	HVAC, PV, building envelope upgrading and the roof retrofit have large energy saving potential.
Cascio et al. (Cascio, Ma, Borelli, & Schenone, 2017)	Apartment building	Australia, 2006	N/A	✓	✓	✓	✓	N/A	N/A	N/A	N/A	✓	N/A	103 kWh/m ²	11 kWh/m ² (89% reduction)	Air tightness improvement and LEDs upgrading are cost-effective retrofit options.
Berardi et al. (Berardi, 2018)	Educationa l office building	Canada, 1931		N/A	✓	N/A	✓	N/A	N/A	N/A	N/A			266 kWh/m ²	NA	Upgrading the building envelope with super-insulating materials poses large energy saving potential.
Liu et al. (Liu, Liu, Ye, & Liu, 2018)	Apartment building	China, 1988	✓	✓	✓	N/A	N/A	✓	N/A	N/A	N/A			408,253 m ³ for natural gas, 144,150 kWh for electricity	357,798 m ³ for natural gas, 94,740 kWh for electricity (34% reduction)	Replacing windows with appropriate materials is a better option than external wall insulation from an economic perspective.

Mora et al. (Mora, Cappelletti, Peron, Romagnoni, & Bauman, 2015)	Apartment building	Italy, 1923	✓	N/A	✓	N/A	N/A	N/A	✓	N/A	✓	N/A	✓	342.1 kWh/m ²	95.9 kWh/m ² (72% reduction)	Solar and photovoltaic system contributed greatly to minimizing energy consumption.
Dahlhausen et al. (Dahlhausen, Heidarinejad, & Srebric, 2015)	Commercial office building	United States, N/A	✓	N/A	✓	✓	✓	✓	N/A	N/A	N/A			313 kWh/m ²	189 kWh/m ² (40% reduction)	Ambitious energy saving targets require the installation of a large number of building components and heating and cooling equipment
Jradi et al. (M. Jradi, Veje, & Jørgensen, 2018)	Educational office building	Denmark, 1930s	✓	✓	N/A	✓	✓	N/A	✓	✓	✓	N/A	N/A	191 kWh/m ²	55 kWh/m ² (71% reduction)	A deep energy retrofit package is recommended considering upgrading the building envelope along with the energy supply systems.
Mauri et al. (Mauri, Vallati, & Ocłoń, 2019)	Apartment building	Italy, 2006	✓	N/A	✓	N/A	N/A	✓	N/A	N/A	N/A			39.5 kWh/m ² for space heating	22.1 kWh/m ² for space heating (44% reduction)	The interaction between user's behaviour and technical management plays a key role in energy reduction and thermal comfort optimization.
Carlsson et al. (Carlsson, Touchie, & Richman, 2017)	Apartment building	Canada, 1990s	N/A	N/A	N/A	✓	N/A	N/A	✓	N/A	N/A			95 kWh/m ² for space heating	46 kWh/m ² for space heating (51% reduction)	Air-tightness and ventilation behaviours have large impacts on the overall energy consumption in cold climates. A heat recovery ventilation system is recommended in cold area.

Charles et al. (Charles, Maref, & Ouellet-Plamondon, 2019)	Office building	Canada 1960s	✓	N/A	N/A	✓	N/A	N/A	✓	✓	✓	✓	N/A	252 kWh/m ²	139 kWh/m ² (45% reduction)	Envelope upgrading are one of the most important parameters in reducing of the building energy consumption.
Fregonara et al. (Fregonara, Verso, Lisa, & Callegari, 2017)	Detached residential house	Italy, 1963	✓	N/A	✓	N/A	N/A	N/A	✓	N/A	✓	✓	N/A	118 kWh/m ² EPC grade E	15.3 kWh/m ² (87% reduction) EPC grade A	The best solution in terms of energy saving does not necessarily accommodate the retrofiting costs saving requirement.

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Table 1 Literature review of previous studies on energy retrofit measure

85 EWI is the external wall insulation; RI is the roof insulation; GR is the glazing renovation; AT is the airtightness improvement; ED is the efficient

86 lighting device; TSC is the temperature sensor and control valve; MVHR is the mechanical ventilation and heat recovery; EE is the Energy efficient

87 household equipment; PV is the photovoltaic panels; SC is the solar thermal collectors; HP is the heat pump and chiller.

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Further observation of Table 1 reveals that previous research hardly investigated the alternative combinations of various ERM s and their impacts on energy saving and carbon reductions. Moreover, since the impact of various ERM s on the primary energy consumption reductions are interconnected, it is not applicable to calculate the overall energy saving potential by linear addition of all the energy saving potential for each individual ERM s without conducting the integrated simulation. For instance, the installations of GSHP will lead to higher electricity consumptions, which on the other hand, could be compromised by the installations of solar PV system. Similarly, due to the complexity and time-consuming simulation process, it is very difficult to model all the possible ERM s combinations at the initial design stage. Thus, it is significantly crucial to adopt a rapid assessment approach to reduce the simulation efforts and aid the decision making process in the planning stage of building retrofit.

Energy performance certification (EPC) has been adopted by most European countries as a Passive House design standard. UK government has set a minimum EPC grade E for the residential and commercial properties with approximately $440kWh/m^2$ annual primary energy consumption, which will affect 18% of commercial properties in England and Wales with house ratings of “F” or “G” (Davidson, 23rd March 2018). As for the Norwegian regulations, the minimum requirement is annually $120 kWh/m^2$ of primary energy consumption for Passive House standard (Skaran, 2013). Although EPC standard is becoming an important energy consumption indicator (Collins & Curtis, 2018; Droutsa, Kontoyiannidis, Dascalaki, & Balaras, 2016; Li, Kubicki, Guerriero, & Rezgui, 2019; Pascuas, Paoletti, & Lollini, 2017) in the real estate market, only few literature (Balaras, Dascalaki, Droutsa, & Kontoyiannidis, 2016; Belpoliti, Bizzarri, Boarin, Calzolari, & Davoli, 2018; Fan & Xia, 2018; Fregonara et al., 2017; Monzón & López-Mesa, 2018) investigated the decision-making process with EPC upgrading as one of the retrofit motivations goals. Besides, few attempts have been made to evaluate the relationships between the retrofit combinations and their EPC upgrading capacity. From the

decision-making perspective, it would be beneficial to adopt a rapid, user-friendly and EPC related approach to facilitate the combinations and selections of various ERMs.

This paper aims to develop a holistic EPC related building retrofit approach for a residential apartment building in Oslo. Based on the existing building condition and pre-retrofit survey, 11 different ERMs are exemplified and grouped into 3 levels energy efficient measures (passive, active and renewable measures) according to the potential amount of energy reduction and carbon emission. With the aim to reduce the complicated and time-consuming simulation process for random combinations of various ERMs, 18 combination packages (COMBs) are selected based on the aforementioned principles (Fabric priority, Renewable in supplement, and Avoid complicated installation process). These COMBs are categorized into 4 levels (Moderate Retrofit-I, II, III, and Extensive Retrofit) with respect to the depth of energy saving potentials defined by EU policy paper (Artola, 2016). The EPC related building retrofit approach is then conducted using in two steps: i) The obtained post retrofit annual primary energy consumptions for the 18 combination packages are ranked according to Norwegian EPC standard. ii) By introducing the novel ELD (Energy Limiting Difference) assessment factor, which only considering the difference of primary/renewable energy consumption in the extreme winter and summer months, the post retrofit EPC standard for each combination package are linked with the difference of maximum and minimum primary energy consumption and available renewable energy. The relationship between ELD assessment factors and relevant EPC grades for the 18 combination packages is plotted and verified against the obtained EPC results from step i). It can be found that instead of performing the annual primary energy consumption with any random retrofit combinations, the novel EPC related building retrofit approach establish a rapid and direct link between EPC grades upgrading and retrofit combination packages with the help of ELD assessment factors, which enables the holistic retrofit assessment for any possible ERMs. Hence, by adopting the proposed EPC related

retrofit approach, the time efforts for the energy simulation is only about 22% of that for conventional approach, which significantly facilitates the rapid retrofit design and decision-making process. This holistic retrofit approach provides useful guidance for the similar apartment block retrofit incorporating renewable energy measures in the cold climate region, and could be replicable for other building retrofit projects in Europe. The structure of this paper is organized as following: Section 2 discusses about the methodology applied in this research at three levels, which are individual ERM level, combination package level and EPC assessment level. Section 3 describes the existing building conditions, simulation hypothesis, baseline building model, the selected ERMs and their combination packages. Section 4 discusses about the primary energy and carbon emission reduction for each selected COMBs. The rapid EPC related retrofit approach using novel ELD assessment factor is also analysed and compared with the conventional approach. The key research findings and future works are summarized in section 5.

2. Holistic EPC Related Retrofit Approach

In this research, the following holistic EPC related retrofit approach (shown in Fig. 1) has been applied: Firstly, a pre-retrofit site inspection is carried out with the aim to identify the existing building post-construction conditions, which aims to collect the essential information for building energy modelling stage. Besides, building occupant survey are conducted to analyse the energy usage patterns and occupancy's behaviours. Secondly, the demo site building model is established in the simulation software (i.e., IES VE) with the local weather data acquired from Energy Plus. Thirdly, the existing annual energy consumption bills will be used to validate and modify the established model. The adjusted model could provide a high degree of accuracy and facilitate the further predication and calculation of energy saving potentials for the various combination packages. Fourthly, at individual energy retrofit measure level, taking into considerations of existing building conditions, local planning permission, a list of energy

retrofit measures ERMs are proposed and grouped into three different categories (passive, active and renewable energy measures). At the ERM combination level, 18 different combination packages are defined based on the building retrofit levels defined by EU policy paper (Artola, 2016). Finally, all the combination packages will be assessed and ranked using the innovative EPC related retrofit approach based on ELD assessment factor, which greatly reduces the simulation efforts and facilitates the retrofit decision-making process.

Fig. 1 Research Methodology of the holistic EPC related retrofit approach

2.1 Individual ERMs level and classification principle

The selected energy retrofit measures (ERMs) are grouped into passive, active and renewable measures, based on the following selection criteria:

- 1) Passive measures: ERMs related to partially changing the building components, including but not limited to upgrading the existing building fabric and service systems with more energy efficient systems, etc.;
- 2) Active measures: ERMs including installation of heating set point schedule, smart meter, efficient lighting system, improving the air tightness of the building, etc.;
- 3) Renewable energy measures: ERMs making use of renewable energy resources, such as ground source heat pump (GSHP), solar PV, solar thermal collector that can be incorporated into the existing building.

2.2 EPC standard selection --- based on ELD assessment factor

The Norwegian buildings can be classified in the range of grade F to A, according to its EPC standard ("Byggeteknisk forskrift (TEK17)," 2017). In order to satisfy the current passive building design code in Norway (Skaran, 2013), EPC level should be at least grade C or above with annual energy consumption less than 110 kWh/m^2 . Based on the simulation obtained annual energy consumptions, the proposed 18 combination packages are ranked according to their EPC grades, which provide clear indications for their annual energy saving potentials. In order to avoid the complicated simulation process with all the possible combination packages, we developed a novel EPC related approach using an assessment factor, i.e, Energy Limiting Difference (ELD), which is defined as the maximum and minimum monthly energy consumption difference over a year for each retrofit combination package. This assessment approach is based on the assumption that the maximum energy reduction potential is relevant to the maximum primary and renewable energy difference over a year for any defined retrofit combination.

Reflecting the energy saving potentials, ELD can be calculated as the differences of two factors, including: 1) the primary energy consumption of the grid imported thermal energy and the grid imported electricity; 2) the renewable energy contributions. The calculation method of ELD is shown in Equations (1)-(7):

$$ELD = \Delta(PE)_{max,m} - \Delta(RE)_{max,m} \quad (1)$$

$$\Delta(PE)_{max,m} = PE_{max,m} - PE_{min,m} \quad (2)$$

$$PE_{max,m} = (PE_{e,max})_m + (PE_{t,max})_m \quad (3)$$

$$PE_{min,m} = (PE_{e,min})_m + (PE_{t,min})_m \quad (4)$$

$$\Delta(RE)_{max,m} = RE_{max,m} - RE_{min,m} \quad (5)$$

$$RE_{max,m} = (RE_{e,max})_m + (RE_{t,max})_m \quad (6)$$

$$RE_{min,m} = (RE_{e,min})_m + (RE_{t,min})_m \quad (7)$$

In these equations, ELD is the maximum monthly energy limiting difference. The assessment factor, i.e., ELD with a smaller value represents better post-retrofit energy performance for the selected COMBs. $\Delta(PE)_{max,m}$ represents the maximum monthly primary energy difference, which consists of two parts i) the difference of the maximum ($PE_{e,max}$) and minimum ($PE_{e,min}$) monthly primary electricity energy consumption; ii) the difference of the maximum ($PE_{t,max}$) and minimum ($PE_{t,min}$) monthly thermal energy consumption. $\Delta(RE)_{max,m}$ represents the maximum monthly renewable energy difference, which is the sum of two parts :i) the difference between the maximum ($RE_{e,max}$) and minimum ($RE_{e,min}$) monthly renewable electricity energy, and ii) the difference of the maximum ($RE_{t,max}$) and minimum ($RE_{t,min}$) monthly renewable thermal energy.

Taking COMB 14 as an example, the process of identifying the ELD assessment factor is shown in Fig. 2. Being the coldest month throughout the year in Oslo, January poses the maximum primary energy consumption with the minimum amount of renewable energy available. In contrast, as the hottest month with sufficient solar energy during a year, June yields the minimum primary energy consumption with the maximum amount of available renewable energy. Therefore, the maximum thermal energy difference is occurred between point 1 ($PE_{t,max}$) and 2 ($PE_{t,min}$), with the maximum electricity difference between point 3 ($PE_{e,max}$) and 4 ($PE_{e,min}$). In terms of renewable energy, the maximum renewable thermal energy difference occurs between points 5 ($RE_{t,max}$) and 6 ($RE_{t,min}$), with the maximum electricity difference between points 7 ($RE_{e,max}$) and 8 ($RE_{e,min}$). The detailed discussion of this approach will be included in section 4.2.

Fig. 2 Representative example of ELD assessment factor calculation

3. Model establishment and selection of combination packages

3.1 Demo site building description

This research will develop a holistic retrofit method for rapid energy upgrading of residential building blocks in the Oslo district, which is supported by EU Horizon 2020 funded project RezBuild ("REZBUILD Project," 2019). The selected demo site building in this research is located at the Bertramjordet condominium in Rosenholmveien, which is approximately 14km from the centre of Oslo. The apartment block No.64 in the Bertramjordet complex was chosen as the demo site building, which is shared with an internal partition wall with Block 63 to constitute a whole apartment block. The southeast and aerial views of the demo site building are shown in Fig. 3 and Fig. 4 respectively. Built in 1987, it was a four-storey apartment block with the unheated basement, top level attic and 12 flats (half of the whole apartment building). The total building floor area is approximately $1839.4m^2$, including heated area of $934.2m^2$ and unheated area of $905.2m^2$. Each flat in this apartment has an average of $77.85 m^2$ dwelling area.

Fig. 3 Southeast view of the demo site building

Fig. 4 Aerial view of demo site building

3.2 Building energy model construction and validation

Several site inspections, surveys and meetings with the Bertramjordet cooperatives (Biswas et al., 2018) were conducted by the project partner OBOS ("OBOS Bastart," 2019) from October 2016 to March 2017. Detailed fabric construction layers, thermal conductivities, and the overall U-value of the building envelopes are summarized in Table 2 (cooperatives, May 2017), which is compared with the maximum U-values according to NS3700 ("Criteria for passive houses and low-energy buildings - Residential buildings," 2013) for Passive houses.

Table 2 Building fabric details of the demo site building (cooperatives, May 2017)

Construction	Thickness	U-value ($W/m^2 \cdot K$)	Maximum U-values according to NS3700 for Passive houses ($W/m^2 \cdot K$)
Parking: floor	270mm	0.50	0.15
Parking: exposed roof	15mm	5.98	N/A
Parking: ceiling	400mm	0.19	0.15
Parking: external wall	280mm	3.43	N/A
Parking area door	10mm	5.88	N/A

External gamble wall	280mm	0.32	0.18
External balcony wall	160mm	0.23	0.18
Glazing		3.13	0.8
Internal partition	205mm	2.19	N/A
Internal ceiling	210mm	0.35	N/A
Flat entrance door	30mm	2.80	0.8
Roof	156mm	0.89	0.13
Attic insulation	420mm	0.18	

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258 Human behaviours including comfortable temperature ranges, occupancy profiles and the
259 household equipment usage patterns are proven to affect the building energy performance
260 significantly ("Standard 55-2013 -- Thermal Environmental Conditions for Human
261 Occupancy," 2013). A post occupancy survey revealed that the current building occupancy is
262 a mixture between retired pensioners and families with children. The occupancy profile was
263 defined with the heating system on during the winter season (from 1st September to 30th May).
264 The current district heating system in the baseline model was considered as 24-7 constant room
265 temperature around 21°C. In the model, two kinds of air exchange conditions including air
266 infiltration and mechanical ventilation were considered. The mechanical ventilation rate of the
267 demo site building was assumed as $8.5 \text{ m}^3 \cdot \text{h}^{-1}/\text{m}^2$ at 50 Pa pressure difference (Engineers,
268 March 2015). Referring to other retrofitting projects in similar climatic condition in Finland
269 (Niemelä, Kosonen, & Jokisalo, 2017), Sweden (Dodoo, Gustavsson, & Tettey, 2017) and
270 Norway (Nord, Løve Nielsen, Kauko, & Tereshchenko, 2018) and the ASHARE guide (Tor
271 Helge Dokka, 2013), the corresponding average ventilation rate is set as 0.85 ACH, including
272 30L/s and 15L/s in kitchen and bathroom, respectively. The air infiltration rate is considered
273 as 0.6 ACH. The space heating and domestic hot water (DHW) of this apartment block are

274 supplied by a district heating system, which is powered waste incineration. The detailed model
 275 input data are summarized in Table 3.

276 Table 3 IES VE model input data or ASHRAE and CIBSE Guide

District heating (cooperatives, May 2017)	Winter: on (temperature maintained constant at 21 °C)	01 Sep to 31 May
	Summer: off	1 st June to 31 Aug
District heating (Francisco Pinto & Carrilho da Graça, 2018; Nord et al., 2018)	Seasonal efficiency	80%
	Heat delivery efficiency	90%
	Average water inlet temperature	10°C
	Hot water supply temperature	60°C
Ventilation (Niemelä et al., 2017) (Baumhof et al.) (Ascione, Bianco, De Stasio, Mauro, & Vanoli)	Mechanical ventilation	0.85 ACH (30L/s in kitchen and 15L/s in bathroom)
	Infiltration	0.6ACH

("Knudsen diffusion,")		
Lighting (Enongene, Murray, Holland, & Abanda, 2017)	Maximum power consumption	4.4 W/m ²
	Luminous energy conversion efficiency	25% of electricity can be converted into luminous
	Schedule	In summer time, peak zone between 6:00-9:00 AM, 20:00-24:00PM; In winter time, peak zone between 6:00-9:00 AM, 16:00-24:00PM
Internal gains (Muhyiddine Jradi, Lecuelle, Høj Madsen, Veje, & Jørgensen, 2017; M. Jradi et al., 2018)	Occupants	90.0W/person of sensible heat, 60.0W/person of latent heat
	Lighting	3.3W/m ²

Fig. 5 Baseline geometry model of the residential block in IES VE

After the building fabric conditions and the model input parameters were defined, the demo site building model (as shown in Fig.5) was established in IES VE. In the demo site building, district heating is the main supply for both space heating and hot water. Three-year district heating consumptions from 2014 to 2016 (shown in Table 4) are used to compare and verify the established baseline model, with the aim to accurately simulate the energy performance for the building.

Table 4 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		

3.3 Baseline model energy simulation results

In the building baseline model, the annual primary energy consumption of the building was calculated as 172kWh/m², which includes 103 kWh/m² of space heating, 43 kWh/m² of electricity consumption, and 26 kWh/m² of DHW. According to Norway EPC standard, this

demo site building will be ranked as F grade, which is far below the current required passive house standard (A, B or C grade) in Norway.

In addition to the annual energy consumption and heat loss, it is useful to analyse the monthly energy consumption of the building to identify the variation of electricity and heating demands. Fig. 6 shows the monthly space heating, domestic hot water and electricity consumption of the building by conducting the simulation in the IES VE software. It is shown that January is the month with the highest energy consumption of about 21.85 MWh, which is the sum of primary electricity consumption from grid and primary thermal energy consumption from district heating. Over the whole year, space heating consumes the most energy compared with electricity and domestic hot water (DHW).

Fig. 6 Monthly final energy consumption profile

3.4 Index of proposed alternative energy retrofit measures (ERMs)

The selected three level ERMs with the detailed technical specifications are summarized in Table 5. All the technical specifications were obtained from the RezBuild project partners, available product manufacturers or technology developers. The technical parameters used in Table 3 are explained below: U_w is the external wall thermal transmittance; U_a is the roof slab thermal transmittance; U_g is the garage slab thermal transmittance; U_{gl} is the glazing thermal transmittance; d is the thickness of the insulation materials; η is the efficiency of the heat recovery system; COP is the efficiency of the solar thermal collector and BIPV panel, EER is the system energy efficiency ratio.

Table 5 Technical specification for selected ERMs

	Energy measures	Nomenclature	Technical specification
Passive measures	Triple glazing	GR	$U_{gl}=0.62\text{W/m}^2\text{K}$
	Garage ceiling insulation	GI	$U_g=0.1\text{W/m}^2\text{K}$, Vacuum insulation panel
	Attic floor insulation	AI	$U_a=0.1\text{W/m}^2\text{K}$, Vacuum insulation panel
	Wall insulation upgrading	WI	$U_w=0.1\text{W/m}^2\text{K}$, Vacuum insulation panel
	Air tightness improvement	AT	EPDM foil system
Active measures	Heat recovery system	HR	Effectiveness: 86%
	Temperature sensor	SP	Temperature set decrease to $2\text{ }^\circ\text{C}$ in winter
	Efficient lighting device	ED	LED lighting with 40% electricity consumption reduction

Renewable energy measures	Ground source heat pump	GSHP	Heat capacity of 18.7 kW, COP: 3.4
	Flat solar thermal collector	ST	Collector area=172.8m ² , Tilt angle 25° Solar heat generation efficiency: 47%
	Building Integrated Photovoltaics	BIPV	A=192m ² , Tilt angle 25°, 28.9kW _p PV electricity generation efficiency:18.8%

314

315 3.5 Retrofit combination packages

316 According to EU policy paper(Artola, 2016), building retrofit levels could be classified into
317 four categories: minor retrofits, moderate retrofits, extensive retrofits and almost zero-energy
318 building retrofits, which corresponds to energy consumption reduction in the range of 0-30%,
319 30-60%, 60-90% and beyond, respectively. Based on the 3 pre-combination principles with
320 “fabric priority”, “renewable in supplement”, and “avoid complicated installation process”.
321 COMB01-COMB04 are combinations with only passive measures, which is referring to the
322 fabric improvement. In the site building, the total wall area is 550.55m² and the glazing area is
323 102.05 m². Therefore, the ratio of window/wall is approximately 18.5%, which results in a
324 large energy saving potential of the glazing retrofit. As shown in Table 6, a total of 18 ERMs
325 combination packages have been categorized into 4 levels: “Moderate Retrofit-I, II, III” and
326 “Extensive Retrofit” according to the 3 pre-combination classification principles. Moderate
327 Retrofit-I” focus on integrating of the passive ERMs into the baseline. “Moderate Retrofit-II”
328 is the combination between the selected active ERMs and passive ERMs. “Moderate Retrofit-
329 III” includes passive ERMs, active ERMs with only 1 renewable ERM. Finally, the
330 combinations of passive ERMs, active ERMs and at least 2 renewable ERMs are considered in
331 “Extensive Retrofit”.

Table 6 Retrofit combination packages

Retrofit Group	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	√	√	√	√	√	√	√	√	√	√	√

4. Retrofit simulation results and discussion

4.1 Primary energy consumption, carbon emission and EPC assessment of ERM combinations

After defining the combination packages in section 3.5, the established baseline model was updated by incorporating the 18 COMBs respectively. For each individual COMB, the monthly energy consumption and the primary energy consumption were simulated. Primary energy consumption is calculated as the sum of thermal energy consumption supplied by district heating and electricity consumption supplied by electricity grid. Besides, the CO_2 emission is calculated by the sum of each energy components multiplied by their different weighting factors. The obtained primary energy consumption and CO_2 emission are presented in Table 7. In general, the maximum possible energy reduction occurs in COMB18 due to the fact that it incorporates all ERMs. Compared with the baseline results, the final energy consumption and the CO_2 emissions of COMB 18 is reduced by 83% to $29 kWh/m^2 \cdot year$ and 88% to $4.2 kgCO_2/m^2 \cdot year$, respectively.

The assessment of EPC grade of all combination packages is summarized in Fig. 7. In “Moderate Retrofit I”, the EPC grade upgrades from F into E, with a maximum final energy reduction of 17% to $142 kWh/m^2 \cdot year$ in COMB04. Therefore, the COMBs in “Moderate Retrofit I” will not be able to achieve the expected energy saving targets for Norwegian Passive house standard. It can be noted that the installation of additional insulation layers on the existing building fabric, and the upgrading of double-glazing with triple glazing is the most promising passive ERM, contributing significantly to the primary energy reduction. Most of the combination packages within “Moderate Retrofit II and III” satisfy the EPC grade B, C and D, with a primary energy reduction of 44% to $96.6 kWh/m^2 \cdot year$ in COMB12. It can be concluded that among “Moderate Retrofit II”, the most promising combination packages is COMB08 which integrates only 4 ERMs (GR+HR+AT+SP) but achieving a 39% of final

energy reduction. Consisting of 4 ERMs (GR+AT+SP+GSHP) in “Moderate Retrofit III”, COMB09 can reduce 77.5% of heating energy with 30% increase of imported grid electricity. COMB12 consists of only 3 ERMs (GR+HR+GSHP), which reduces 71.0% of heating energy with 40% increase of imported grid electricity. Hence, it is obvious that GSHP system can drastically improve the energy efficient of the building. The “Extensive Retrofit” combination packages match well with EPC grade A, with a maximum final energy reduction of 83% to $29 \text{ kWh/m}^2 \cdot \text{year}$ in COMB18. It should be noted that COMB14 and COMB15 are integrated with ST and BIPV, which will be affected by the intermittent feature of solar radiations. Whilst COMB16 is integrated with AT and SP, which is more stable. Therefore, both AT and SP should be considered before installing renewable ERMs. Further observation of Fig. 7 reveals that COMB09 yields the best energy performance among “Moderate Retrofit III”, which is even comparable with some of combination packages in “Extensive Retrofit” (e.g. COMB13). Meanwhile, two threshold lines presented in the Fig. 7, which represented for the Passive House energy limit and low-energy house limit, with maximum annually 120 kWh/m^2 and 56 kWh/m^2 (Tor Helge Dokka, 2013) respectively. Besides, only COMB17 and COMB18 have the ability to reach the low-energy house limit (Tor Helge Dokka, 2013) with at least 67% of the total energy reduction in this demo site building, which proves that the passive, active and renewable energy measures have to be integrated in one packages to realise the low-energy house standard.

From the perspective of carbon reduction, COMB 09, 13-18 could satisfy with the Norwegian passive house standard ("Byggteknisk forskrift (TEK17)," 2017; Thullner, 2010), with the maximum CO_2 emission less than $15 \text{ kgCO}_2/\text{m}^2 \cdot \text{year}$. Considering the number of ERMs incorporated, COMB09, COMB12, COMB13 and COMB15, which include a maximum of 4 ERMs should be the most energy efficient packages compared with other COMBs. COMB09 includes totally 4 ERMs, especially containing the improvement of air tightness and

temperature set point control, while the other combinations in “Moderate Retrofit-III” is less than 4 retrofit measures. Besides, improvement of air tightness and temperature set point control have a higher energy saving potential than most of the passive and active retrofit measures, with 14.7% and 7.3% respectively. Therefore, although all the combinations in “Moderate Retrofit-III” includes ground source heat pump (GSHP), only COMB09 reach a lower primary energy consumption with 84.9 kWh/ m² year. Amongst these combination packages, the commonly shared individual ERM’s are GR, HR, GSHP and BIPV. Therefore, it could be concluded that these four individual ERM’s play more significant roles for primary energy saving than other ERM’s, which should be highly recommended.

Table 7 Simulation predicted performance of various COMBs

Combination packages	Energy consumption for heating and domestic hot water EP_h (kWh/ m² year)	Energy consumption for electricity EP_e (kWh/ m² year)	Primary energy consumption EP(kWh/ m² year)	Equivalent CO2 emission (KgCO2/m² year)
Baseline	129.1	42.5	171.6	33.9
Moderate Retrofit-I: only include passive measures				
COMB01	105.6	42.6	148.2	28.8
COMB02	103.7	42.6	146.2	28.3
COMB03	118.4	42.6	160.9	31.6
COMB04	99.4	42.6	142	27.4
Moderate Retrofit-II: include both passive measures and active measures				
COMB05	88.6	44.8	133.4	25.3
COMB06	99.0	30.2	129.2	25.7

COMB07	72.5	30.2	102.6	19.9
COMB08	59.1	44.8	103.9	18.8
Moderate Retrofit-III: include 1 renewable energy measure and other passive/active measures				
COMB09	28.9	56.0	84.9	13.6
COMB10	54.7	58.1	112.8	19.6
COMB11	52.4	60.0	112.4	19.3
COMB12	37.4	59.2	96.6	15.9
Extensive Retrofit: include 2 renewable energy measures and other passive/active measures				
COMB13	29.0	55.5	84.4	13.6
COMB14	29.0	43.2	72.1	12.4
COMB15	37.4	36.0	73.4	13.6
COMB16	15.0	57.2	72.2	10.7
COMB17	15.0	34.0	49	8.4
COMB18	0.3	28.8	29.1	4.2

Fig. 7 The relationships between primary energy consumption and (EPC) for the 18 retrofit combination packages

4.2 EPC related retrofit approach

As described in section 2.3, a novel EPC related holistic retrofit approach featuring a novel assessment factor (ELD) has been applied in this research with the aim to reduce the amount of simulation time involved in conventional retrofit approaches. The novel assessment factor - Energy Limiting Difference (ELD), is defined as the difference between the maximum and minimum monthly net energy consumption, which can be obtained from the energy consumption in the coldest winter month and hottest summer month respectively.

In order to verify this approach, 3 groups of combination packages (COMB05&08, COMB11&12, COMB13&15) have been chosen with their monthly thermal, electricity consumptions and renewable energy generations plotted in Fig. 8-10.

It can be found that, in general, all the combination packages show the same trend, with the maximum and minimum electricity, thermal energy consumption and the available renewable energy occurred in the coldest (January) and hottest (June) month respectively. This further

410 demonstrates the possibility to conduct the energy consumption simulations for two months
411 (the coldest and hottest) and obtain the ELD assessment factor, which will then linked with
412 EPC grades.

413 As shown in Fig. 8, with ELD of $11.5 \text{ kWh/m}^2 \cdot \text{mon}$, COMB05 is classified as EPC grade
414 D. While COMB 08 fits into EPC grade C, with reduced ELD value of $8.25 \text{ kWh/m}^2 \cdot \text{mon}$.

415 Similar EPC upgrading can also be observed in Fig. 9 which shows the retrofit simulation
416 results with combinations of HR and GSHP in COMB11, and combinations of GR, HR and
417 GSHP in COMB12. With ELD of $11.42 \text{ kWh/m}^2 \cdot \text{mon}$, COMB11 can be categorized as EPC
418 grade D. While COMB 12 fits into EPC grade C, with reduced ELD value of $8.91 \text{ kWh/m}^2 \cdot$
419 *mon*.

420 Furthermore, by comparing COMB12 (Fig. 9) and COMB13 (Fig. 10), one additional ERM
421 (ST) has been included in COMB 13 in comparisons with the existing ERMs in COMB 12 (GR,
422 HR and GSHP). Without changing the building thermal behaviour, COMB13 utilizes the on-
423 site generated renewable thermal energy, which enables its EPC upgrading to grade B
424 compared with grade C in COMB12. As noticed, the overall ELD in COMB12 of
425 $8.91 \text{ kWh/m}^2 \cdot \text{mon}$ will be reduced to $5.93 \text{ kWh/m}^2 \cdot \text{mon}$ in COMB13, with 33.4% of
426 primary energy saving in the coldest month. Therefore, installation of ST plays crucial roles in
427 upgrading EPC from Grade C to B.

428 By replacing ST in COMB13 with BIPV in COMB15, it would be interesting to investigate the
429 EPC upgrading potential by switching the solar thermal energy into solar electric energy. As
430 shown in Fig. 12, COMB15 will be upgraded to EPC grade A comparing with EPC grade B
431 for COMB13. Analysing the ELD difference, it is easy to find that the overall ELD
432 ($5.93 \text{ kWh/m}^2 \cdot \text{mon}$) in COMB13 will be reduced to $5.79 \text{ kWh/m}^2 \cdot \text{mon}$ in COMB15,
433 with 2.3% of primary energy saving in the coldest month. Therefore, it could be concluded that

among the two available renewable resources, solar electric energy plays more important role for EPC upgrading in comparison with solar thermal energy.

Fig. 8 Monthly analysis of EPC upgrading from D (COMB05) to C (COMB08)

Fig. 9 Monthly analysis of EPC upgrading from D (COMB11) to C (COMB12)

Fig. 10 Monthly analysis of EPC upgrading from B (COMB13) to A (COMB15)

Additionally, the conventional approach which needs to perform the 12-month energy consumption simulations for a typical year requires 190 seconds simulation time. Compare with that, this ELD-EPC related approach only needs to calculate the maximum and minimum energy consumptions and available renewable energy in two months (the hottest and coldest) during one year period, with significantly reduced simulation time of only 42 seconds. Therefore, the ELD assessment factor can be considered as a unique indicator to identify the EPC grades, which significantly facilitates the retrofit decision-making process with reduced simulation times.

Applying the EPC grades (shown in Fig. 7) from the conventional approach into the ELD assessment factor (shown in Fig.11) identified from this novel approach, a range of ELD values have been linked with the relevant EPC grades for the proposed COMBs, as shown in Table 8. All the combination packages with ELD values more than $11.42 \text{ kWh/m}^2 \cdot \text{month}$ cannot match with the EPC C grade, indicating a further need for deep retrofiting. The most recommended COMBs which better facilitate the EPC upgrading are also summarized in Table 8. For this specific research, the baseline ELD assessment factor is $18.06 \text{ kWh/m}^2 \cdot \text{month}$, which falls into EPC grade F. With recommendation of GR based passive retrofit combinations,

the ELD values in the range of 13.58 to $14.02 \text{ kWh/m}^2 \cdot \text{month}$ indicating EPC grade E. With recommendation of ‘GR + HR’, the ELD in the range of 11.42 to $12.65 \text{ kWh/m}^2 \cdot \text{month}$ indicates EPC grade D. EPC grade C is matching with ELD in the range of 8.25 to $9.49 \text{ kWh/m}^2 \cdot \text{month}$, with typical retrofit recommendation of ‘GR + HR + GSHP’. Besides, the indication of EPC grade B correlated to ELD value in the range of 8.25 to $9.49 \text{ kWh/m}^2 \cdot \text{month}$, with typical retrofit recommendation of ‘GR + AT + SP + GSHP’. Finally, the EPC grade A requires the ELD within -0.42 to $5.79 \text{ kWh/m}^2 \cdot \text{month}$, with retrofit recommendation of ‘GR + SP + GSHP’ + BIPV’ combination.

Fig. 11 The relationship between EPC grades and ELD assessment factors

Table 8 EPC upgrade indication with ELD ranges and retrofit recommendations

EPC grade	ELD ranges ($\text{kWh/m}^2 \cdot \text{month}$)	Annual Primary energy consumption (kWh/m^2)	Recommended ERM
F	15.92 - 18.06	160-200	GR
E	13.58 - 14.02	135-160	

D	11.42 - 12.65	110-135	GR + HR
C (minimum requirement)	8.25 - 9.49	95-110	GR + HR + GSHP
B	5.93 - 6.74	75-95	GR + AT + SP + GSHP
A	-0.42 - 5.79	56-75	GR + HR + GSHP + BIPV
Low energy house (Tor Helge Dokka, 2013)	-0.42 - 1.15	<56	GR + AT + HR + SP + GSHP +BIPV

5. Conclusion

This paper presents a novel holistic EPC related retrofit approach which links the possible combination packages with their post retrofit EPC grades. This approach is based on the ELD assessment factors, thereby facilitating the rapid yet accurate retrofit decision-making process. A low-rise apartment block in Oslo was chosen as the demo site building. Employing the simulation engine of IES VE software with the weather data acquired from Energy Plus, a novel simulation methodology was adopted: i) After analysing existing baseline building features and environmental conditions, eleven passive, active and renewable energy retrofit measures (ERMs) with specific technical parameters were firstly determined. ii) Based on the three principle of “Fabric priority”, “Renewable in supplement”, and ‘Avoid complicated installation operation’, these ERM were then combined into 18 combination packages, which were categorized into four levels: “Moderate Retrofit-I, II, III” and “Extensive Retrofit” according to EU policy paper (Artola, 2016). A translation from the EPC standards to a user-friendly assessment factor (ELD) and corresponding energy saving ranges for the proposed COMBs are concluded, with the following conclusions drawn from this research:

- 1) Retrofit combination level ‘Moderate Retrofit-I’ (only passive measures) indicates the

potential energy saving range of 6% to 17%, which do not satisfy the minimum grade C of EPC requirements.

2) Retrofit combination level ‘Moderate Retrofit- II’ (passive measures + active measures) represents the potential energy saving range of 22% to 40%, with part of the COMBs satisfying the minimum grade C of EPC requirements.

3) Retrofit combination level ‘Moderate Retrofit- III’ (passive measures + active measures + GSHP) indicates the potential energy saving range of 34% to 51%, with the proposed COMBs satisfying the EPC grade C and B.

4) Retrofit combination level ‘Extensive Retrofit’ indicates the potential energy saving range of 51% to 83%, with all the COMBs satisfying the EPC grade B and most of the COMBs reaching EPC grade A.

This research showcases a novel rapid and user-friendly EPC upgrading assessment approach with a range of defined ELD assessment factors. Different from the conventional time-consuming approaches that need to simulate the annual total energy consumptions, the proposed approach in this research simplifies such process by only considering the maximum and minimum primary energy consumption and available renewable energy in two extreme months (coldest and hottest). The case study in Oslo further helps to verify the feasibility of this ELD-based EPC assessment approach, which draws a relationship between the ELD assessment factor and the relevant EPC grades. Such approach provides a theoretical support that can greatly facilitate the rapid retrofit design and decision-making process in the future. By applying ELD-based EPC approach for the selection of ERMs, it could be concluded that among the two available solar energy resources, solar electric energy plays more important role for EPC upgrading in comparisons with solar thermal energy. Finally, considering the number of ERMs incorporated, three COMBs with a maximum number of four ERMs are recommended for Oslo retrofit project, including: COMB12 -

‘GR+HR+GSHP’ (reduction of 44% primary energy consumption and 53% carbon emission,), COMB09 - ‘GR+AT+SP+GSHP’ (reduction of 51% primary energy consumption and 60% carbon emission), and COMB15 - ‘GR+HR+GSHP+BIPV’ (reduction of 57% primary energy consumption and 60% carbon emission). By applying these 3 COMBs, the post-retrofit energy performance will match with EPC grade of C, B and A respectively, which provide a wide range of possible solutions for the decision makers using such EPC related retrofit approach. This novel holistic EPC related approach will serve as a useful guidance for similar retrofit projects incorporating renewable energy measures in Oslo district and other high-density area in cold climate region.

This paper focuses on the ELD-based EPC assessment approach for retrofit decision-making process in cold climate area. However, in other climate Zone, the results might be dependent on climatic conditions as well as the existing building fabric and service system conditions. Therefore, future work will be concentrated on further validation of such ELD-based EPC assessment approach in a diverse range of climate conditions.

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