An overview of holistic approach to achieve net zero energy residential building retrofit

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Abstract: This review focus on the holistic approach technologies and strategies of energy-efficient residential building retrofitting. Besides, energy balance between both energy demand side and renewable energy supply side are discussed with the integration of different renewable energy technologies, such as advanced insulation, high efficient heat pump, solar aided energy system, combined heat and power plants, dynamic control strategies. Moreover, this review especially focused on the retrofitting problems and challenges of traditional residential buildings which is mostly built before 1960s, which accounts for 14.5% of the overall CO_2 emission based on 2015 levels. Combined with these retrofit technologies, several reference residential building cases in Europe are analysed, indicating six main problems from pre-retrofit simulation to retrofit operation process that obstacle the retrofitting performance. To bridge the performance gaps, this review discussed the building performance simulation models and optimization algorithms. The optimization function have mathematical characters of multi-objective, multi-variability, multi-disciplinary, multi-constrained (4M) with discrete, non-linear characteristics. Applying the optimization strategies model is an essential to build a deep understanding between building performance simulation (BPS) and building performance optimization (BPO), which help engineers to make an optimised holistic retrofitting decisions.

Keywords: traditional residential building, retrofit optimization, holistic approach, NZEB, performance gap

1. BUILDING RETROFIT INTRODUCTION

The European Commission had set climate strategies for 2020, 2030 and 2050 in their relatively climate and energy packages. For a promising future, according to climate and energy package action, there are three main steps: 1) by the end of 2020, greenhouse gas emission will be reduced by at least 20% compared with 1990 level (Capros, 2012); 2) For the mid-term, by the end of 2030, greenhouse gas emission should be reduced 40% compared with 1990 level (Höglund-Isaksson, 2010); 3) For the long-term, by the end of 2050, the target of the greenhouse gas emission is to cut 80% based on 1990 level (COMMISSION, 2011), which implies that at least an average of 2% of greenhouse gas emission reduction must be realized to fulfil the final target. Take the UK for example, the UK government set itself a 60% reduction of carbon dioxide target on 2000 levels by 2050. And the residential sector accounts for around 23% of the UK's total energy consumption (Statistics, 2017). As it is calculated, 63% of properties were built before 1960s, which is also categorized to the historic and traditional buildings. That means these kinds of dwellings accounts for 14.5% of overall greenhouse gas emission by 2015 levels. To be more visually understand the meaning of 80% of greenhouse gas emission reduction, a specific example is a must. Taking the CO_2 emission as an example, according to statistics, the averaged emissions baseline in 1990s level is about $97\mathrm{kg}CO_2/m^2 \cdot year$, which is taken from a semi-detached house with area of $80m^2$ (Change, 2015). If the target is set to reduce 80% of the emissions, the final CO_2 emission value will be no more than 19.4 $\mathrm{kg}CO_2/m^2 \cdot year$ in 2050. If the target is set to reduce 90% of the emissions, the final CO_2 emission value will be no more than 9.7 $\mathrm{kg}CO_2/m^2 \cdot year$ in 2050.

The first concept of ZEB goes back to the 1970s. Esbensen and Korsgaard (1977) describe the Experimental Zero Energy Building. It denoted that the Zero Energy House is dimensioned to be self-sufficient in space heating and domestic hot-water supply during normal climatic conditions (Esbensen and Korsgaard, 1977). It was 2007 when a broad discussion about ZEB began because of the increased concern about climate change and energy resource shortages. The UK was the first country to provide an original definition of zero carbon homes in late 2006. According to the definition, a "zero carbon home" has zero net emissions of carbon dioxide from all energy use in the home including heating, lighting, hot water and all other energy use (DCLG, 2006). At the same time, a discussion about the definition of Zero Energy Building occurred in the USA, which is defined as follows: A net zero energy building is a residential or commercial building with greatly energy needs reduced through efficiency gains such that the energy needs can be supplied with renewable technologies (Torcellini, 2006).

From a global perspective, the International Energy Agency (IEA) has provided two definitions, for Net Zero Energy and Zero Carbon Buildings. Net Zero Energy Buildings address that these buildings are energy-neutral over a year period. Zero Carbon Building address that these buildings are carbon-neutral over a year period, which do not use energy that results in net carbon dioxide emissions. In addition, most definitions only include operational energy, ignoring the embodied energy, which consists all of the processes associated with the production of a building because of the absence of an efficient and accurate methods to calculate the embodied energy. ZEB categories according to the produced energy amount:

I. Energy Plus building
II. Autonomous Zero Energy Building
III. Net Zero Energy Building
IV. Near Zero Energy Building

2. HEAT PUMP SYSTEMS COMBINED WITH SOLAR ENERGY

2.1 Solar boosted heat pump

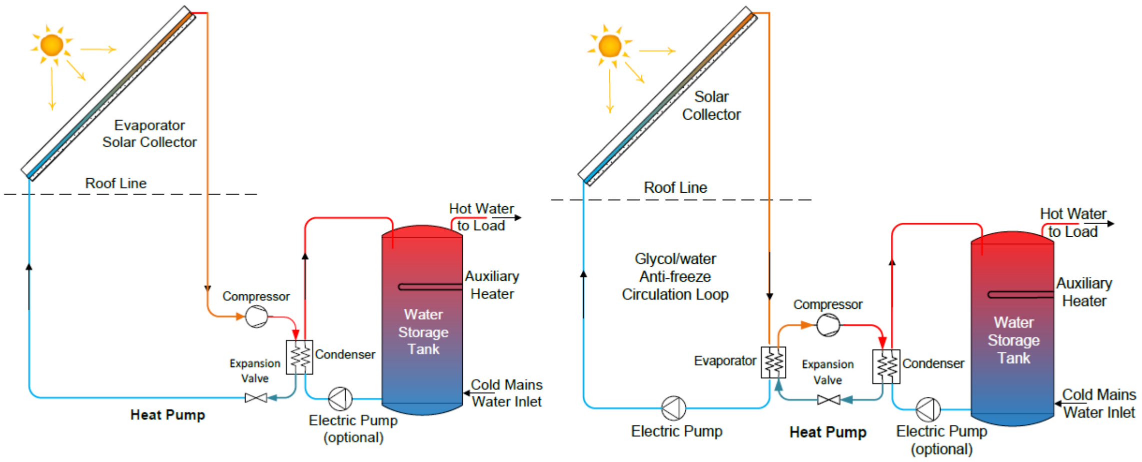
Solar PV panels can convert solar energy to electricity output with efficiency of approximately 15%, and the balance of the solar energy dissipated into environment as thermal heat. Thus, we can use the waste solar thermal heat and the electricity from the PV panels to boost the work of Heat pump systems. Especially, during cold ambient periods, the solar thermal collector can collect the low-grade heat from the incident solar energy, and serves as an evaporator to boost the temperature of the working fluid in the evaporator. In this way, the heat pump cycle can transfer heat from low-grade solar collector to thermal storage in a form of high temperature. Sankey diagrams can calculate the energy performance of the PV/thermal boosted Domestic water heating. In the calculation, the COP of the direct solar boosted heat pump can reach up to 4.2, and the system efficiency up to 3.64 (Harrison, 2017). According to the recent literatures, there are two main approaches that emerged in the commercial market:

I. Direct expansion SB-HPWH system

For the direct-expansion approach, refrigerant is circulated directly through the solar collectors (O'Dell et al., 1984, Y.W. Li, December 2007, Ito et al., 1999, Ito et al., 2005, Kuang and Wang, 2006, Chow et al., 2010). And the absorber of the solar collector becomes evaporator directly. However, the main risks are the leakage of traditional refrigerants and high installation cost.

II. Indirect SB-HPWH system

For the indirect solar boosted-heat pump system, the working principle is similar to direct ones, the solar collector is connected to the evaporator of heat pump as heat exchanger in the close system. This is especially used in much colder areas where the antifreeze heat transfer fluid cannot be directly contact with the cycle of domestic water storage (Kong et al., 2018, Y.W. Li, December 2007, Chow et al., 2010, Kuang and Wang, 2006). Although the installation is simplified, there are the additional components, such as the electric heat pump and the heat exchanger. The example of (a) direct and (b) indirect SB-HPWH configurations are shown in Fig. 1 (Harrison, 2017).



(a) (b)

Fig. 1 The example of (a) direct and (b) indirect SB-HPWH configurations

2.2 Dual-mode or Tri-mode heat pump solar collector

To realize the reliable supporting of the thermal energy for both the space heating and domestic water heating by renewable energy. Jacob van Berkela, Onno Kleefkensb and Felix Lacroixc put forward a novel control strategy for connection of PV/thermal solar collector, ground heat source to one heat pump systems depending on the heat demand of the users. The configuration of the connection system is shown in Fig. 2.

Overall efficiencies for GSHPs are inherently higher than that of the air source heat pumps, because ground temperatures are relatively stable and higher than the mean air temperature in winter and lower in summer. The majority of heat pump output temperature is ranged in 50-55℃, and no more than 65℃. Commercially used products usually performance with COP of 4 in space heating, and COP of 2.75 in domestic water heating. Also, the lifespan of GSHP is expected to be 20-25 years, and the ground coil will lasts for 50 years. One of the main challenges is the cost of such GSHP systems. Taking the example of SLINKY systems. The capital costs for horizontal installed ground source to water heat pump systems will cost around 600-1150£/KW, and 850-1500£/KW for vertical installed systems.

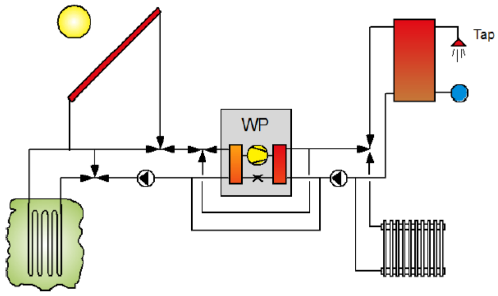


Fig. 2 configuration of the connection of PV/Thermal collector and ground source heat exchanger system

3. OTHER HYBRID SYSTEMS

3.1 Hybrid photovoltaic and thermal PV/T technology

Photovoltaic is been widely used recently in different applications with an electricity efficiency in markets arranging from 12%-19% (Wikipedia, 2018) for inorganic PV panels, and 3%-15% (Yu, 2014) for organic photovoltaic panels. Company SUNPOWER can produce a type of solar cell with high efficiency, which is up to 21.5% (Sunpower, October 2015). Besides, there are three main problems that challenge the development of PV panels: (1) Relatively high initial investment and low electricity output; (2) Dust and other particles that accumulated on the surface of the panels will reduce the electricity efficiency; (3) Overheating of the PV panels will result in electricity degradation. The efficiency of a solar cell declines by about 0.25%-0.5% for every 1 degree Celsius increase in temperature (Nižetić et al., 2016).

Many investigations have been made to explore the solutions to both dust accumulations and cooling technologies. Besides common improvements, there is a possibility to improve the overall performance of PV panels by integrating the PV and thermal collector, which is also called the PV/T technologies. According to the results, there is an improvement of 16.3% of the overall increase in electricity output (Nižetić et al., 2016). The water-based PV/thermal technology, which enhanced solar electrical and thermal efficient by 9.1% and 42%, respectively (Zhang et al., 2013). In another study, a simple passive automatic cooling and cleaning system using thin film of water is developed for standalone PV system (Elnozahy et al., 2015). This study figures out a 29% increase in electricity fields, together with 45.5% and 39% reduction in temperatures of the front and rear faces of the module, respectively. Besides, current PV/Thermal cost are approximately 3-5 times that of standard PV modules, however it is expected that these prices will drop as volume and competition increases in the market (Harrison, 2017).

3.2 Solar collector combined domestic water heating

The solar energy from the sun reaches the earth in the radiation form. When the radiation is absorbed by surface of solar collector, it transfers and stored as thermal heat, and usually stored with the water heating. As we know, solar water heating is the cheapest storage method, which will replace almost 20% of heat consumption for a family. Literatures (Jayamalathi, January 2012, Bhowmik and Amin, 2017) indicate that the flat solar collector usually have 50% of thermal efficiency without reflector, and 60% of thermal efficiency with reflectors. Thus, the overall efficiency of the flat plate solar collector is increased approximately 10% by using the reflector. Another investigation to improve its efficiency is focused on solar radiation concentration, which is also called as concentrating solar collectors. And it will reaches a higher temperature level. A typical concentrated solar collector typically has a collector, tracking system, absorber, heat transferring liquid and an energy storage system.

3.3 Hybrid CHP systems

Another innovative hybrid CHP systems for high temperature heating plant in existing buildings are investigated by Livio de Santoli, Gianluigi Lo Basso and Benedetto Nastasi (de Santoli et al., 2017). To produce high temperature heat water along with the electricity generation, four types of energy plants were designed and compared. They are listed as below:

I. Separated generation, Fig. 3(a)
II. Traditional CHP and boiler, Fig. 3(b)
III. Combined CHP and 2-stage heat pump system, Fig. 3(C)
IV. Combined CHP, CO_2-HP, PV/T and boiler system, Fig. 3(d)

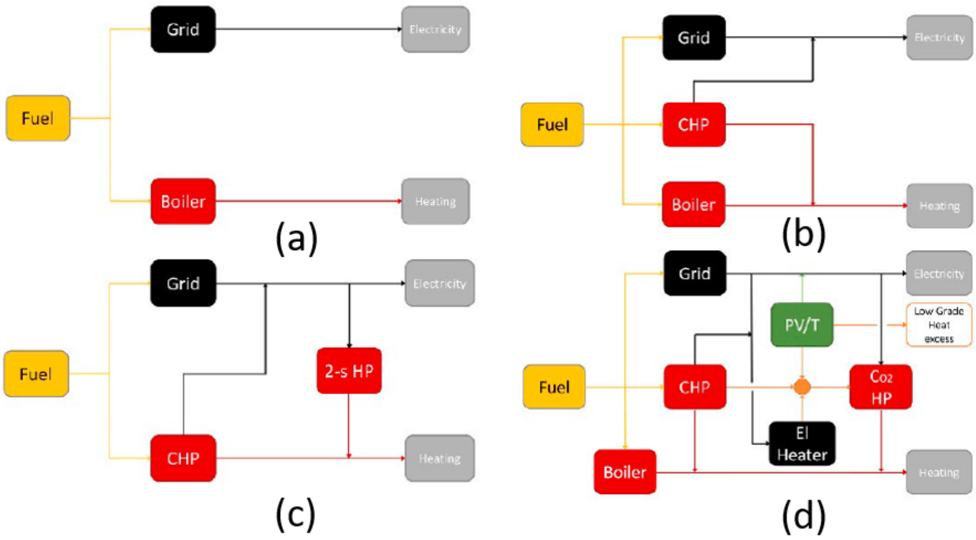


Fig. 3 four types of energy plants

The first energy scenario is composed by separated heat and electricity parts, which is directly support electricity from grid and heat from boiler. The second energy scenario is composed by traditional CHP systems, which means that CHP and grid together support electricity, and boiler together with the waste heat of CHP to support heat. The third energy scenario is composed of grid, CHP and two-stage heat pump. The CHP can drive partial or total two-stage heat pump to support heat to the users. And partially generated electricity along with grid electricity to support electricity to users. In the fourth energy scenario, it is more complicated, with an addition boiler as a back-up, CHP waste heat along with CO_2 heat pump to realize heating requirement. At the same time, the hybrid PV/T solar collector will support the low-grade heat requirement of the CO_2 heat pump. With increasing of the PV/T heat production, the electric heater will operate within the thermal storage device to support the operation of the CO_2 heat pump. Similar to the third scenario, electricity is supported by grid electricity, CHP and PV panels. The experiment results indicate that when PV/T contributes 80% of the total energy as heat to drive the low-grade CO_2 heat pump, the equivalent primary energy of the whole systems can be reduced by 68.35%.

4. UNCERTAINTIES OF BUILDING ENERGY PERFORMANCE RELIABILITY

During the process of building retrofit towards net zero energy buildings concept, recognition of optimization is a necessary improvement for complex NZEBs. Form the abstracted mathematically perspective, this kind of optimization is even more difficult and time-consumption, regarding multi-disciplinary systems including passive and active envelop insulation, daylight, natural ventilation, HVAC, heat and electricity storage, micro-CHP, biomass boiler, heat pump, PV, PV/T, solar collector, and micro- wind turbines and so on. Therefore, the optimization of historic and traditional residential building energy-efficient retrofitting can be concluded with the following mathematical properties of multi-objective, multivariate, multi-disciplinary, multi-constrained (4M) with discrete, non-linear characteristics. And analysis of these characters is crucial for developing a deep understand of integrating building performance simulation (BPS) and building performance optimization (BPO).

Nowadays, the popular optimization algorithms can be classified into three main areas: (1) enumerative algorithms, (2) deterministic algorithms, (3) stochastic algorithms. Especially, in the last decades, genetic algorithms (GA) and evolutionary algorithms (EA) are the most efficient stochastic algorithms for the optimization problems in building energy design (Congradac and Kulic, 2009, Attia et al., 2013, Meyarivan, 2002). Literatures also mentioned many BPO tools namely GenOpt, MATLAB, modeFrontier, Topgui, EnergyPlus and so on (Attia et al., 2013, Wu et al., 2017).

Many literatures mentioned that there is often a significance performance between the simulated energy prediction and the operational measured energy pre- and post- building retrofit. This performance gap has become an increased concern recently with the requirement of large amount of energy efficient building retrofitting, especially for those house owners with self-funded building renovation. As house owners, they are wondering what kind of the energy level that their house could reach with a reasonable investment before energy retrofitting, and what it exactly will be after the renovation. With the development of automated meter reading technology, the performance gap becomes more and more visible, which help us make a better understanding of the cause of this phenomenon. As can be seen in the retrofit case study, there are lots of new development of monitor technologies, such as cheap sensors, radio-frequently identification (RAFID) tags, and ubiquitous positioning, which can provide high resolution results to measure the operational energy performance. There are three main categories that cause the performance gap: the design stage, the construction stage, the operational stage (de Wilde, 2014), which can be summarized in the following parts. And in many cases, there is a combination of several issues.

In design stage, the main problems are: (1) Inefficient communication about performance targets for the future building between clients and design team; (2) Inefficient energy saving systems; (3) Fundamental uncertainties, such as actual weather condition, occupancy schedule, internal heat gains, and plug loads (4) Inefficient alignment between design and prediction

In construction stage, the main problems are: (1) Insufficient attention to both insulation and airtightness; (2) Potential risks for the creation of thermal bridges that can change the overall performance; (3) Actual construction does not meet specification

In operational stage, the problems are: (1) uncertainties in experimental data; (2) Occupant behaviours are often different from the design stage; (3) Lack of standardization and continuity of monitoring, analysis, and control throughout the building life cycles

Therefore, there are two main prediction methods: Firstly, one of the most used prediction method is first-principle model. According to the known building physics and building systems, a physical model is developed, which will be translated into a computational model. And once it is solved, the prediction is generated. Plus, there is also more precise prediction with more details, which develops into dynamic energy simulation. The dynamic means the indoor and outdoor conditions will vary dynamically with a time step in simulation. The second prediction method is black box approach. This is based on developing input parameters and output parameters without explicitly modelling the system and physical processes. This approach is broadly known as machine learning and covers techniques such as regression analysis, artificial neural networks, and support vector machines. And the training data can be supported by either experimental tests or first-principle model. Thus, further investigation is proposed to develop a solid approach on model calibration:

I. Further quantify the performance gap range dependent on the time and contextual factors.
II. Taking into account the uncertainties to specific simulations, and making sensitivity analysis.
III. Capturing measured data that can not to be fully predicted, decompose the performance gap and making a further study.
IV. Deep study of machine learning approaches will provide a better baseline for a much accurate prediction based on first-principle simulation.
V. Deep study of large sets of buildings, where each building has specific prediction and experiment data on the similar design or similar performance.

5. CASE STUDY RESEARCH AND RETHINKING

This review collected and investigated eight different residential retrofitted cases, except for the case 7, which is an efficient energy-plus constructed recently as zero energy building in German. The investigated cases mainly focus on residential buildings that is funded by the house owners of European countries, including Denmark, UK (England and Wales), Belgium, German and Finland (Fig. 4). The UK cases represent western north-Atlantic climate. The Denmark and Finland cases represent northeast subarctic and tundra climates. And the German and Belgium cases represent central continental climate. However, for these cases, there is a lack of collection of south mediterranean climate such as Italy and Croatia. Furthermore, these cases contain four European residential building typologies, including single-family houses (detached or semi-detached house), terraced houses, multi-family houses, and apartment blocks.

These cases implied several different levels of retrofit technologies, including element retrofitting and holistic retrofitting. From the investigation of these cases, many lessons can be concluded and described as below:

I. In case 1, a saving of about 50% on the energy consumption for heating confirms that there is a large potential for achieving energy saving in the insulation part of the building stock through renovation as the first step of building retrofit before applying other active and renewable energy measures.

II. Only focus on the simple economic and energy savings achieved through renovation, there will be a problem of neglecting the increased market value of the house

III. Without enough consideration and prediction of indoor environment quality in both case 2 and case 3, pollutions such as CO_2 concentration will easily exceed the standard, which will not meet the satisfy standard of the house owners. Although the energy performance is much better than before the renovation, the indoor environment is poorer than before.

IV. As the analysis in case 5, with considering of primary energy consumption to be compensated by production on site, the retrofitted dwellings should need a large amount of sustainable energy supplied by generator, such as thermal heat collector, PV panels, wind turbines, micro-CHP. However, take the example of PV panels only. If all compensated energy has to be suppled in this case, it need 77 m^2 totally in case 5. Whereas, there is no enough places for PV panels to mount on the pitched roofs.

V. Another problem with zero energy building concept is the time lag between primary energy consumption and renewable energy production, as is shown in case 5. However, case 6 tried to solve this problem with battery storage and on-grid and off-grid strategies. The results indicate the investment of battery is still high.

VI. Case 8 indicates that a domestic scale CHP is not the best approach to realize NZEB in Finland. However, applying local shared biomass CHP is a better solution, because of its high overall efficiency and power to heat ratio in the large scale system.

VII. Among case 1 and case 6, energy performance gaps occurred in different scales. A further deep understanding of the performance gaps is urgent and significant to improve the reliability of the post-retrofit performance. The performance gaps is described is Fig. 4 for each cases.

6. CONCLUSION AND FUTURE WORK

This literature review focus on the holistic approach of energy-efficient residential building retrofitting. It begin with the basic introduction of CO_2 emissions target in 2015 and UK residential building market stocks, which especially stressed dwellings built before 1960s that accounts for 14.5% of the overall CO_2 emission based on 2015 emission levels. Then the review discussed different ZEB definitions and their characters. Furthermore, the energy demand side is been analysed with the application of current building envelop insulation and the advanced future materials. Then, the renewable energy supply side is been analysed with the on-site and off-site renewable energy technologies, including heat pump, solar energy, combined heat and power plants. Moreover, this review especially focused on the retrofitting problems of historic and traditional buildings which is mostly built before 1960s. To solve these problems, the building performance simulation and optimization is introduced and discussed. The optimization of historic and traditional residential building energy-efficient retrofitting has the mathematical properties of multi-objective, multivariate, multi-disciplinary, multi-constrained (4M) with discrete, non-linear characteristics. To have a deep understand of integrating building performance simulation (BPS) and building performance optimization (BPO), it is essential to build dynamic mathematical model under different condition limitations.

Case number	Case name	Building details	Retrofit measures	Energy performance	Gap level	Payback time	Reference
1	Danish single-family house	Built in 1965, single-family house, 160m^2, 2-4occupants	New gas boiler, electrical convectional heater, heat pump, wood burning, MVHR, LED	Final energy consumption reduced by 23% Heating consumption after retrofitting reduced by 53%	+5%	Payback time 36 years	[26, 27]
2	Danish 3 multi-story apartment blocks	Built in 1969, apartment blocks, 5293m^2, 66 flats	District Heating, MVHR, air supply control, daylight, energy saving bulb with auto-off control, PV systems(30,000KWh/year)	Heating consumption after retrofitting reduced by 31.5%	+27%	Payback time 14 years	[28]
3	Low energy retrofit in UK – a Victoria solid wall house	Built in Pre-1919, 76.9m^2, 2 occupants, end-terraced house	High efficiency boiler, MVHR, LED, Daylight, passive clothes drying, Solar PV, Solar thermal collector	CO_2 emissions reduced by 43% (reduced from 40 to 23 $(kgCO_2)/m^2 \cdot yr$	+28%	Not mentioned	[29]
4	Low energy retrofit in UK – a Modern 1990s cavity wall	Built in 1992, 84m^2, 2-4 occupants, mid-terraced house	High efficiency boiler, natural ventilation, LED, passive clothes drying, Solar PV, daylight, solar thermal collector	CO_2 emissions reduced by 40% (reduced from 76 to 46 $(kgCO_2)/m^2 \cdot yr$	+34%	Not mentioned	[30]
5	Energy efficient retrofit of an end of the row house in Belgium	Built in 1957, 78.3m^2, 2 occupants, self-detached house	High efficiency with built-in pump, a stack driven ventilation system, small electrical radiator in the loft room, 2.75m2 solar boiler with remained electrical boiler, 120l water tank, programmable thermostat, 8.7m2 PV panels	Final energy reduced by 67% in space heating, 48% in DHW	+27.7 %	Payback time: 19 years	[31]
6	Five energy retrofit houses in South Wales	Built in Pre1919, 1950s, 1960s and 2000s, 67-86m^2, 2-5 occupants, semi-detached houses	2.5-4.5KWp PV panels, 4.8-18KWp lead acid battery/ 2-3.97KWp lithium-ion battery, gas boiler/combi-boiler, MVHR	CO_2 emissions reduced arranging from 49%-74% Final total energy consumption reduced arranging from 15%-52% Energy saving improved with up to 56% reduction in space heating and up to 84% reduction in electricity	- 15.3%	Payback time: 50-60 years	[32]
7	Efficient House Plus in Berlin	130m^2, 2 storeys, single-family detached, 4 occupants	98m^2 PV panels (efficiency 15%), 73m^2 thin-film PV (efficiency 12%) Central heating system with air-to-water heat pump, floor heating systems, mechanical ventilation with 80% heat recovery, auto switch-off smart control system, 40KWh buffer battery (second hand battery cells)	Energy use: total final energy consumption will be 61.1KWh/$m^2\cdot yr$ Electricity surplus will be 4.5KWh/$m^2\cdot yr$ Photovoltaic energy generation will be 65.5KWh/$m^2\cdot yr$	Not mentio ned	Not mentioned	[33]
8	Two single family NZEB in Finland	150m^2, one story house, single-family detached, 4 occupants	4 modules-2.874m^2 each solar plate collector, PV modules 93Kwh/m^2a 100KWe Direct Combustion Indirect Fired Gas Turbine Ground Source heat pump 1KW thermal boiler+50Lwater storage 500L hot water tank for both space heating and DHW Radiator heating using both hot water and electricity	Compared with standalone house, total heating demand of passive house decreased by 57%, and total electric demand decreased by 5%, DHW reduced by 35.3% and 47.2% relatively, in standalone and passive house.	Not mentio ned	Not mentioned	[34]

Fig 4: Case study collection

This overview also summarized eight reference residential building cases in Europe. There cases indicate many real problems that obstacle the retrofitting performance. These performance gaps from simulation and construction are discussed and formed into future works. With the reduction of the performance gaps, the retrofit process will get a more optimized solution, which help to achieve a higher energy level certificate.

In future work, the following aspects need to be further investigated:

I. Explore an efficient and accurate method to calculate the embodied energy
II. Develop holistic energy efficiency retrofitting strategies for the whole building, results in the optimization to reduce energy consumption refers to the integration of renewable energy systems, avoiding the oversize of the system.
III. More attention should be focused on visual, fabric and culture value characters of historic and traditional buildings, to get a better understanding of the performance gap with calibration from the measurement-based methodology.
IV. In the northern countries of Europe, utilizing on-site solar energy as a renewable energy resources to achieve annual balance of NZEB may face many obstacles, such as the mismatching between the energy production and consumption with the limited area of roof and façade, especially in the dense city areas. This situation encourages the investigation of using micro and small-scale biomass-based combined heat and power systems as energy systems to achieve NZEB balance. Thus, there should be a criteria between on-site and off-site decision.
V. The difficulty of defining a building retrofit boundary when CHP systems are combined as a retrofit technology.
VI. Understanding the occupancy behaviours before renovation may positively affects the post-retrofitting performance reliabilities.

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