Modular facade retrofit with renewable energy technologies: the definition and current status in Europe

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Abstract: Over the last decade, a number of research and innovation projects have started developing modular facade retrofit solutions which integrate on-site renewable energy technologies. Although there are a growing number of academic articles and demonstration projects showcasing their achievements, the overview of current status and development trend are missing. It is difficult for policymakers, the public and fellow researchers to understand the evolution of modular facade retrofit technologies and who are the important players in the field. As a part of the ongoing European Commission Horizon 2020 project team, the authors decided to write this review article that meets the above needs.

Due to the lack of clarification in previous studies, this article firstly introduced and defined the term of Modular Facade Retrofit with Renewable energy technologies (MFRRn), then provided its classification and the review of recent evolution. The MFRRn refer to the retrofitting process that thermal insulation, solar and wind harvest technologies are integrated with the exterior finish of building using modular approach. According to our definition, the MFRRn should fulfil four basic aspects: work to be conducted on existing buildings, work to be undertaken on the facade, using a modular approach, and integrating renewable energy technologies during the retrofit.

This study then reviewed 173 research projects funded under the European Commission the seventh Framework, the Horizon 2020's Energy Efficient Buildings programme, the International Energy Agency Energy in Buildings and Communities (IEA EBC) Annex 50 'Prefab Systems for Low Energy/High Comfort Building Renewal' project, the European Cooperation in Science and Technology (COST) Action TU1403 'Adaptive facades network'. The review shows that at least 14 European Commission research projects and 4 case studies mentioned in COST TU1403 and IEA Annex 50 have involved in certain of level of MFRRn development. Their research progress, timeframe, funding scale and funding flow to nations and contributions from key institutes are analysed. Finally, the current challenges regarding the MFRRn developments and implementations are discussed, and future research focus is proposed.

1. Introduction

Following the recent agreements between European Parliament, the Council of Ministers and the European Commission, the European Parliament has confirmed in November 2018 new 2030 targets of at least a 40 % reduction in domestic greenhouse gas emission (compared with 1990 levels), at least 32% share for renewable energy and at least 32.5% improvement in energy efficiency (compared with 2007 baseline). To achieve these legal binding targets, collective efforts in carbon reduction and renewable energy generation are needed to decarbonise the existing building stock.

The Energy-efficient Building Public-Private Partnership scheme was launched in December 2008 under the European Commission's seventh framework and the Horizon 2020 programme. It aims to develop affordable breakthrough technologies and solutions at building and district scale. Until February 2019, around 600-million-euro European Union budget has been allocated for 173 project consortiums to tackle the challenges in carbon reduction and renewable energy generation. The partners from private sectors within the consortium also made an additional 30% match-contribution to these projects for their research and innovation activities.

Under the Energy-efficient Building scheme, a specific challenge of integrating energy harvesting at building and district level have been identified by the European Commission as one of the key priorities for research and innovation development. A number of research and innovation projects are supported through this scheme from 2008. Together with partners in the International Energy Agency Energy in Buildings and Communities (IEA EBC) Annex 50 project (2007- 2010) and COST TU1403 (2014-2018), key players from Europe have started developing modular facade retrofit solutions which integrate on-site renewable energy technologies.

Although there are a growing number of academic articles and demonstration projects showcasing their achievements, the overview of current status and development trend are not clear. It is difficult for policymakers, the public and fellow researchers to understand the evolution of modular facade retrofit technologies and who are the important players in the field. As a part of the ongoing European Commission Horizon 2020 project team, the authors decided to write this review article to fulfil the gap that there is no single journal article to summarise the current status and development trend of modular facade retrofit with renewable energy technologies in Europe. This article also targets researchers and policymakers based outside Europe but interested in similar development and research in their countries and regions. The current status in Europe, challenges, research focus and research method should be valuable for international audiences.

2. Method

To achieve greenhouse gas emission 2030 target, renewable energy and energy efficiency target, European Commission's seventh framework and the Horizon 2020 programme supported 173 innovation projects related building energy efficiency, including a number of research projects which decided to utilise building facade as a breakthrough to improve the building energy efficiency[1-15]. A clear trend can be found in these projects that modular approaches and renewable energy technologies are starting to be integrated into the building facade retrofitting.

This state-of-the-art review aims to improve the convenience and visibility for the public and researchers by forming the definition of Modular Facade Retrofit with Renewable energy technologies (MFRRn) and systematically analysing the recent innovations on this subject supported through major European funding schemes. A rigorous definition and precise classification not only can explain a new item in simplified words that help people to understand its meaning but also help set up the boundary of a scope which makes further studies easier.

However, such definition and classification are not always available in the dictionary, search engines, databases and previous literature because of its newness or restrictions on access to the document. Besides, many researchers in this field do not provide the definition of the terms and scope of study in their articles. The underline assumption is that the readers understand the meaning of the terms, which not always the case. In many occasions, studies were meant to be conducted for Modular Facade Retrofit, but case studies on modular technology for new buildings were referred. Another common example is that study was meant to be on building integrated renewable energy technologies on a facade, however, roof-integrated renewable energy technologies were presented. The misuse, inconsistent, and inadequate understanding can lead to serious inconvenience for follow researchers and broader audiences.

Therefore, this article is firstly focused on the evolution of facade and definitions of known items, such as, module, modularity, modularisation, modular facade, modular facade retrofit and building integrated renewable energy technologies. A modified Grounded Theory (Confluence-refinement method) is utilised to form the term of Modular Facade Retrofit with Renewable energy technologies (MFRRn). Grounded Theory, developed by Barney Glaser and Anselm Strauss[16,19], has been widely used to build a conceptual framework for phenomena that are linked to multidisciplinary bodies of knowledge[17]. Applications[18-21] of Confluence-refinement method can be found in the social sciences, engineering and architectural researches. The method uses inductive thinking to generate theory from facts and data[22,23], and it is also regarded as context-based, process-oriented description and explanation of the phenomenon[24,25]. The evolution of known items and its classification set the foundation for forming the definition of Modular Facade Retrofit with Renewable energy technologies (MFRRn).

The article then analysed the 173 innovation projects based on four fundamental aspects: facade, modularity, retrofit and renewable energy sources. An organisational network analysis was conducted for the 14 project consortiums which are directly related to the concept of Modular Facade Retrofit with Renewable energy technologies (MFRRn). Statistics on total funding received by each country and organisation, the number of projects involved by a single organisation, and their expertise are summarised. This could help policymakers, the public and fellow researchers understand the evolution of modular facade retrofit technologies and who are the important players in the field.

Finally, this article discussed the technical, financial and social challenges in implementing the Modular Facade Retrofit with Renewable energy technologies (MFRRn). It also proposed a number of future research focuses including a three-layer organisational network analysis approach to help building owners, developers, design teams and suppliers to find the latest Modular Facade Retrofit and Renewable energy technologies and their supply chains locally.

3. The evolution of concept and definitions

3.1 Evolution of facade

The definition of facade is developing continuously. The Dictionary of Construction, Surveying and Civil Engineering 2012[26] claim that 'facade' is 'the external face of a building, usually the front' of the building. According to the ISO 6707-1:2017 definition[27], it is often referring to the 'exterior surface of a wall enclosing a building, usually non-loadbearing, which can include a curtain wall, cladding, or other exterior finish'. It can be noticed that 'usually the front' in the Construction, Surveying and Civil Engineering has no longer emphasised in ISO 6707 standard. Similarly, Herzog *et al*[28] stated that the facade could be classified into load bearing and non-load bearing in terms of structural view. This is contradictory with the definition from ISO 6707 standard in term of a loadbearing element.

From the view of the material, the facade can be classified into metal, glass, concrete, masonry, plastic and timber [29]. The brief evolution history of the facade has been summarised by Knaack et al.'s book [30] and illustrated in figure 1. In recent studies, a clear trend can be found that facade gradually becomes an integrated complex system that is made of modular components with different functionalities, such as shading, ventilation, view, appearance and energy generation. Therefore, it is necessary to capture the advantages and benefits of moving towards modular components.

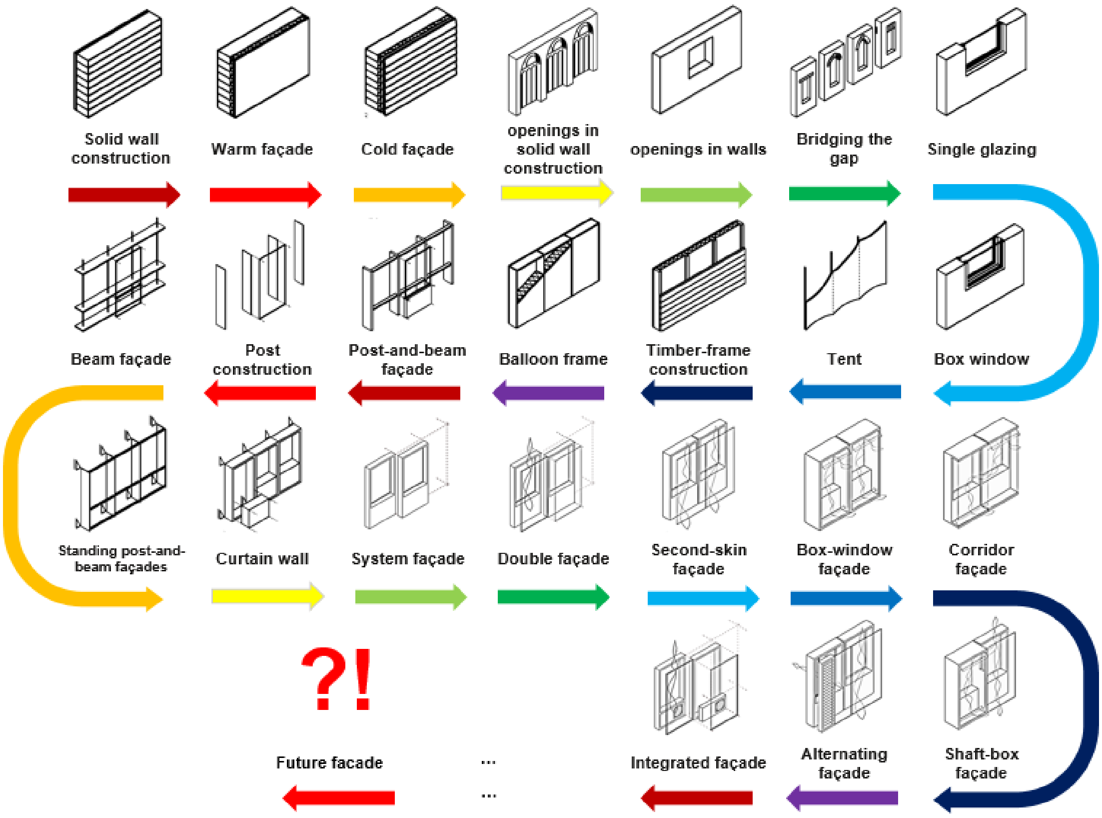

Figure 1 The brief evolution history of the facade (reproduction from Knaack et al.'s book [30])

3.2 Module, modularity and modularisation

Miller and Elgard [31] provided the clarification on the concepts of module, modularity and modularisation based on Miller's studies [32]. A module 'is an essential and self-contained functional unit relative to the product of which it is part. It has standardised interfaces and interactions that allow the composition of products by combination'[31]. Modularity 'is an attribute of a system related to structure and functionality'[31]. It often refers to the degree of flexibility that a system's components may be separated and recombined. Modularisation 'is the activity in which the structuring in modules takes place' [32].

Although modularity has raised a lot of attention in recent years, the concept originated from Marcus Vitruvius Pollio's book detailing the proportions and symmetry in building temples and columns during the ruling of Roman Emperor Augustus. The original meaning of module (Latin word *modulus*) was a standard measure ensuring the right proportions. The German architect Walter Gropius created the modern concept of modular construction during the Bauhaus era (1919-1933), and further elaborated in the 1960s. During that time, building blocks were designed according to standard and used prefabricated materials.

Based on the theory from Kamrani et al. [33], Miller and Elgard [31], the key advantages of modular construction can be evidenced in its standardisation, simplicity, flexibility and customisation. Standardisation process can significantly reduce the cost by avoiding reinventing (which is time-consuming and expensive), enable mass production, make it easier for training, support and problem-solving. Simplicity is mainly referring to the reduced structure in organisational management. For example, the modular process could enable the establishment of independent working units and parallel working on different components which speed up the manufacture or installation process. Flexibility is often reflected during in-use stage which involves maintenance, upgrade or removal. The modular feature can dramatically reduce the time and resources needed for these tasks. The interchangeable parts of modular components and its adaptability in shape and size can also offer customised design solutions. Above advantages triggered the evolution of facade from solid wall construction to modular system.

3.3 Modular facade

The modular building facade was firstly patented by American inventor Lore Brown in 1974[34]. This patent provided an aesthetically attractive solution to connect roof with supporting beams using a plurality of interlocking sectionalised sleeves. Following the invention, a series of patents have been filed to protect the methods of prefabricated buildings[35,36] and its construction[37]. Although these patents are protecting intellectual property and have guaranteed the benefits to the inventors and their companies, they also built barriers for others. In 2008, the concept of the open modular facade was introduced by Hövels[38] at Delft University of Technology. It blended the open-source spirit into modular facade design to create interchangeable, multifunctional, flexible modules that match the demands of occupants.

Modular Facade (MF) is often referring to the exterior finish of building made by modules that have different functions, and possibly come from different suppliers. These modules should have standardised interfaces for future maintenance and upgrade. Few other terms have been used in academic papers to emphasis on a particular feature of the facade. For example, Multifunctional Façade Module (MFM)[39] highlights its functionality. Responsive Building Elements (RBEs)[39] and advanced integrated facades (AIFs)[39] indicate that building envelope is responsible for controlling the energy and mass flows between the building and the outdoor environment. Originated from COST Action TU1403 - Adaptive Facades Network, Adaptive Facade (AF) [40] or Climate Adaptive Building Shells (CABS)[41] refer to building envelopes that can adapt to the changing climatic conditions on daily, seasonally or yearly basis. Its adaptability is often evidenced by responding to external climatic conditions and more importantly meeting occupants' requirements. The adaptability could be achieved through active elements such as the movement of panels, passive components such as bespoke designed shading/ventilation units, environment and energy control system or combinations of above.

It can be noticed that functionality, adaptability and modularity are the key features of modern Modular Facade (MF). The functionality and adaptability are mainly to fulfil the needs of occupants, clients and architects, whereas the modularity is primarily to satisfy the needs of manufacturers, installers and maintenance teams.

3.4 Modular facade retrofit

The purpose of building retrofitting can generally be classified into four categories: aesthetics upgrading[42], acoustic retrofitting[43,44], energy efficient retrofitting, and hazards mitigation retrofitting[45]. Aesthetics and acoustics are often driven by the owner or occupants' needs and involve work on internal or external of buildings. Energy efficient retrofitting is often driven by low carbon agenda, thermal comfort and economic reasons. The retrofit work can involve thermal insulation[46], energy storage[47], integration of renewable sources[48], upgrade or new installation of shading and lighting[49], solar reflection[50] and HVAC[51]. The retrofit for hazard mitigation is an action taken to reduce or eliminate long-term risk to people and property from hazards such as floods[52], hurricanes[53], seismic[54], fires[55,56], indoor air pollutants[57] and outdoor air pollutants[58].

The Dictionary of Construction, Surveying and Civil Engineering states that retrofit is the strengthening, upgrading, or fitting of extra equipment to a building once the building is completed[26]. The process is also called refurbishment or renovation in some countries. The European Economic and Social Committee Multilingual Glossary also provided a vivid definition that it is an act of renewing and overhauling all elements of a building to bring it to a condition that makes it seem as if it is new again, giving it a second useful life [59]. They emphasise that any work on uncompleted buildings is not in the scope of building retrofitting.

Drawing from the definitions of Modular Facade (MF) and Retrofit, the definition of the Modular Facade Retrofit (MFR) can be concluded as the process of strengthening, upgrading, or fitting of extra equipment to exterior of the existing building using modules that have different functions, and possibly come from different suppliers.

3.5 Building integrated renewable energy technologies

According to the US Energy Information Administration's definition, renewable energy is energy from sources that are naturally replenishing but flow-limited. They are virtually inexhaustible in duration but limited in the amount of energy that is available per unit of time[60]. Twidell and Weir[61] defined it as the energy obtained from naturally repetitive and persistent flows of energy occurring in the local environment. There are six major types of renewable energy sources include biomass, hydropower, geothermal, wind, solar and ocean energy, such as tide and wave[62]. In the urban environment where most of the buildings are located, devices for harvesting solar and wind power can be integrated with building facade to meet the local thermal and electrical demand. Biomass, hydropower, geothermal and ocean energy are more challenging to integrate with buildings due to the space needed and size of equipment.

Over the past forty years, a range of applications[63,63] including solar thermal collectors, photovoltaic modules or combinations of above has been utilised to generate heat and electricity for the buildings. Solar thermal systems can offer heating/cooling, hot water supply, power generation from solar heat and improvement of the insulation and overall appearance of buildings. According to the heat transfer medium, solar thermal systems can be classified into air-based, hydraulic-based (water/heat pipe/refrigerant) and PCM-based systems[64]. Building Integrated Photovoltaics (BIPV) refers to building components that are incorporating the PV module into building as a source of electrical power. The component can be roof elements and facade elements[65,66]. Building Attached Photovoltaics (BAPV) refers to PV arrays that are mounted on the existing buildings as a source of electrical power[65]. BIPV often replaces a building component without extra mounting components. BAPV is an independent functional component which needs extra mounting components to add-on to the existing building. Building Integrated Photovoltaics/Thermal (BIPVT) system is a hybrid system combing building integrated thermal collectors and building integrated PV. The system can produce both electrical and thermal energy for the building[67]. Comparing to standalone systems, BIPVT system can be more efficient than individual solar thermal system or BIPV system using the same area of building envelope. This is because heat collection can also reduce the operating temperature of the PV panel which leads to the improved efficiency on PV panel[68].

Although Building Integrated Wind Turbine (BIWT) are not as popular as BIPV, the innovation and demonstration of BIWT have never stopped. Notably, the Bahrain World Trade Centre building integrated three 225 kW commercial-scale turbines on bridges spanning the twin towers. The Pearl River Tower in Guangzhou, China installed four vertical-axis turbines in the middle of the building. Park et al. [69] used computational fluid dynamics analyses to explore three possible installation locations of large-size wind turbines and two possible installation locations of small-sized wind turbines. Despite that noise, vibration, safety, cost and lack of real performance data which become the significant rolling-out barriers at large scale, Park et al. [69] concluded that BIWT is a promising environment-friendly energy production system for urban areas.

3.6 The definition of Modular Facade Retrofit with Renewable energy technologies (MFRRn)

Following the method of Grounded Theory[17], the previous five sections have explained the concepts of the facade, modularity, modular facade, modular facade retrofit and building integrated renewable energy technologies. They made a conceptual framework for the term of Modular Facade Retrofit with Renewable energy technologies (MFRRn) which this article is trying to define.

As illustrated in figure 2, the definition of the MFRRn originated from the commonly understandable term of the facade. It firstly excludes non-modular facade, then excludes the modular construction for new buildings, and finally excludes modular facade retrofit that does not involve renewable energy sources. After the classification and exclusion of related topics, the concept of MFRRn has been narrowed down to a specific scope. The process of narrowing down is illustrated in the red line in figure 2. The evolution of the known terms gradually forms the supporting evidence for the following definition.

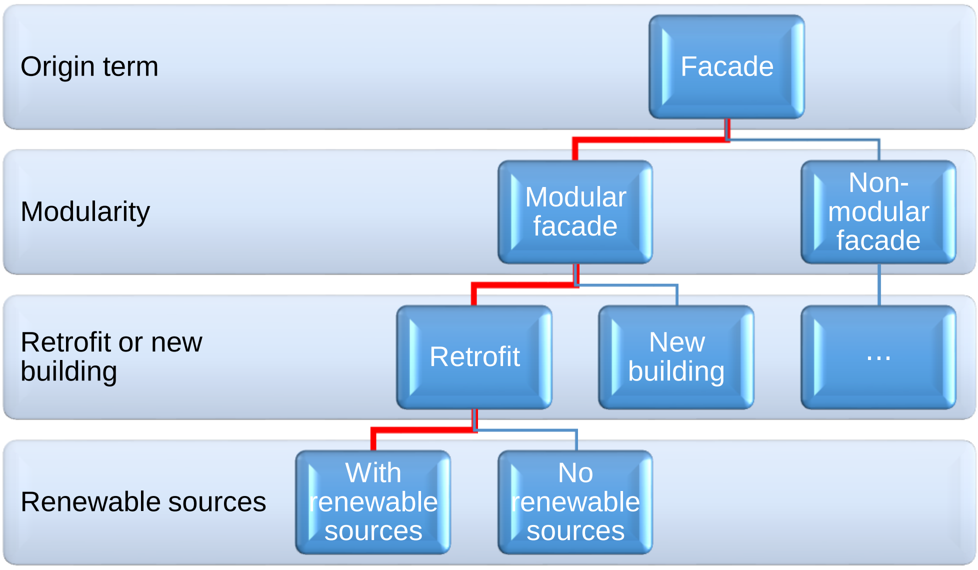

Figure 2 Narrow down the concept of the facade

As the results of the concept evolution and scoping study, the definition of the Modular Facade Retrofit with Renewable energy technologies (MFRRn) is, therefore, given as a retrofitting process that thermal insulation, solar and wind harvest technologies are integrated with the exterior finish of building using modular approach. According to our definition, the MFRRn should fulfil four basic aspects (four corners in figure 3): work to be conducted on existing buildings (retrofit), work to be undertaken on the facade (facade), using modular approach (modularity), and integrating renewable energy technologies during the retrofit (renewable energy). The scope of MFRRn involves a type of facade, four types of retrofit purposes, two types of renewable sources and all factors related to module design, as illustrated in figure 3.

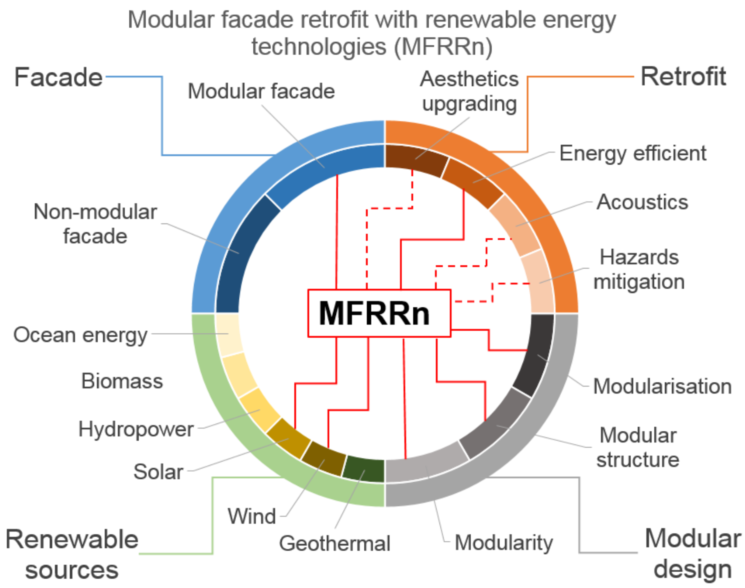

Figure 3 MFRRn concept

Although the primary purpose of MFRRn is to improve the energy efficiency of a building and reduce carbon emission, other purposes of retrofitting, such as acoustic, aesthetics upgrading and hazards mitigation, can also be achieved as the by-products of MFRRn (dot lines in figure 3). For example, the fire resistant and sound insulation can be achieved through applying thermal insulation material which meets the fire and sound requirements[44,56]. The colour and textiles of BIPV can be customised to satisfy the requirement of the aesthetics upgrading. As mentioned in the previous section, it is difficult for facade modules to harvest ocean energy, biomass energy, hydropower and geothermal energy, because geometrical conditions restrict the use of these renewable sources. Besides the size and weight of the equipment are not suitable for applications on building facade. Therefore, the current scope of MFRRn does not include these renewable sources.

4. Current status of MFRRn development and key players

4.1 Current status of MFRRn development

The Austrian Institute for Sustainable Technologies initiated the IEA ECBCS Annex 50 'Prefab Systems for Low Energy/High Comfort Building Renewal' in 2007. With the inputs from industry partners and international partners, the Annex has published a series of reports on Retrofit Strategies, Retrofit Module Design Guide, and Case studies during 2010-2012. The Retrofit Module Design Guide[1] presented four different approaches on how prefabricated renovation modules could be designed and produced. These MFR approaches are developed by four teams from Austria, France, Portugal and Switzerland. The Swiss solution is semi-prefabricated. Their module design is focused on windows, and opaque facade and the finish of the facade are conducted on site. The Austrian solution used a full-story height prefabricated glazing facade. The French solution focused on large vertical metal frame and the treatment of thermal bridges. The Portuguese solution concentrated on smaller size panels based mountable modules. In their Austria demonstration project (Dieselweg 3-19, Graz), solar thermal collectors have been integrated with roof and facade using a modular approach. This forms the early design concept of Modular Facade Retrofit with Renewable energy technologies (MFRRn).

Under the European Commission's seventh framework and the Horizon 2020's Energy-efficient Building programme, around 600-million-euro budget has been allocated for 173 project consortiums to tackle the challenges in carbon reduction and renewable energy integration until February 2019. Within these projects, fourteen research and innovation action projects have involved the activities of the facade developments, modular retrofits and integration of renewable sources on buildings.

The acronym name of these projects, starting time, duration of the project, number of participants, values of these projects, load-bearing materials and the integrated renewables used in these projects are summarised in table 1. The full name and short descriptions of these project are listed in the Abbreviations section of this article. These projects started between 2012 and 2018 with a duration of 3.5-5 years. The size of projects ranges from 4 to 10 million euros. These projects generally have 8 to 20 participating organisations from at least three European countries.

Table 1 European Research and Innovation projects related to MFRRn concept

Project name	Start time	Duration	Number of participants	Load bearing materials	Integrated renewables
MEEFS RETROFITTING[2]	2012-01-01	60 Months	17	Fibre Reinforced	Advanced Passive Solar Protector, Energy Absorption Unit,

				Polymer (FRP)	Advanced Passive Solar Collector and Ventilation Unit, BIPV
RETROKIT[3]	2012-09-01	48 Months	20	Aluminium Timber	Solar thermal, PV
HERB[4]	2012-10-15	42 Months	19	Aluminium	Photovoltaic-solar thermal (PVT)
ADAPTIWALL[5]	2013-09-01	48 Months	8	Lightweight concrete with Nano additives	Solar thermal, PV
MORE-CONNECT[6]	2014-12-01	48 Months	19	Timber Steel	Solar thermal, PV
BRESAER[7]	2015-02-01	54 Months	19	Fibre Reinforced Concrete Steel Aluminium	Solar thermal, PV
BERTIM[8]	2015-06-01	48 Months	15	Timber	Solar thermal
4RinEU[9]	2016-10-01	48 Months	13	Timber	Solar thermal
PLUG-N-HARVEST[10]	2017-09-01	51 Months	13	Aluminium	Solar thermal, PV
RenoZEB[11]	2017-10-01	42 Months	20	Metal	BIPV or BIPVT
HEART[12]	2017-10-01	48 Months	16	Unclear	Solar thermal, BIPV
Envision[13]	2017-10-01	54 Months	13	Metal Timber	Solar thermal, PV
EnergyMatching[14]	2017-10-01	54 Months	16	Unclear	Solar thermal, BIPV
ReCO2ST[15]	2018-01-01	42 Months	17	Unclear	PV

In general, the technological solutions of Modular Facade Retrofit with Renewable energy technologies (MFRRn) have been advanced dramatically over the past decade due to the support from the European Commission and investments from companies. Most of the projects related with MFRRn have undertaken seven stages of development: conceptual design and decision support, modular facade structure and fastening system, thermal insulation and fixing, renewable module integration, safety testing and regulatory compliance, energy management system and user interface, and finally demonstration and evaluation. Not all projects have completed all seven stages, but they may place emphasis on one particular phase of the development due to timing and resources. For example, the early projects have made significant progress in decision making using dynamic simulation software EnergyPlus to explore the whole system performance. During 2013-2017, the frame material, fastening methods, architectural design and the selection of renewable modules have become viable. Limited safety testing and regulatory compliances have also been performed internally within these projects. The demonstrations began within a laboratory environment, and gradually been applied to a part of a building, a full building and multiple buildings.

While having the breakthrough in technological developments in early projects, the consideration in business models and circular economy perspectives have become the core parts of recent projects (such as 4rinEU and PLUG-N-HARVEST). Obtaining trademark, licensing, leasing models and peer-to-peer trading have been proposed. The related ICT platforms, which enable the trading and circular economy analysis, are the core part of ongoing development in the field.

In addition to the fourteen projects mentioned above, there are another nine Framework 7 and Horizon 2020 projects also focused on the development of facade retrofit solutions. According to the public available reports and articles, they might not fulfil all four elements of the MFRRn (Modular design, Facade, Retrofit and Renewable sources, as illustrated in figure 3), but they have focused on at least three elements of the four. For example, the MF-RETROFIT[70], BuildHEAT[71], Heat4Cool[72] and Pro-GET-OnE[73] projects did not adopt the modular design approach, but their works target facade retrofit and integration with renewables. The EASEE[74], A2PBEER[75], E2VENT[76], EENSULATE[77] and REnnovates[78] projects do not involve the integration of renewables on facades; instead, they have worked on the roofs. These projects also contribute to some aspects of MFRRn development. The knowledge and lessons learned from projects can also be transferred to advance MFRRn solutions.

4.1.1 Frame and modular integration

It can be noticed that timber, steel, aluminium, Fibre-Reinforced Polymer and concrete (with Nano additives) have been used as materials for load-bearing in these projects. Out of the fourteen in table 1, five projects have published their modular facade design concepts in their reports or related journal articles. Their design concepts, as illustrated in figure 4, could be categorised as three types: layer-based modular system, frame-based modular system and the combination of two.

The major difference between layer-based and frame-based MFRRn down to the way that insulation material and renewable components are fixed to existing façade. The layer-based approach is to attach supporting structure, insulation material and renewable components one layer by another. The ADAPTIWALL project (top-left in figure 4) adopted a layer-based modular system which utilises a concrete layer to bear the structural load.

For the frame-based approach, insulation material and renewable components are both surrounded by grid frames. These frames directly fixed on the existing facade or the levelling concrete layer which helps deal with uneven surfaces of existing buildings. The MEEFS RETROFITTING, 4rinEU and PLUG-N-HARVEST projects (illustrated at the bottom of figure 4) have adopted a frame-based system that use aluminium, fibre reinforced polymer or timber frames to hold the multi-functional modules that provide warmth and energy generation.

Each type of modular facade retrofit systems has its advantages and disadvantages. For example, the layer-based system can avoid the thermal bridge, but its heavyweight feature is not suitable for high-rise building retrofit. The frame-based system could potentially reduce the weight and thickness of the wall; however, depending on the material used, the frame could become the thermal bridge which reduces the efficiency of the new facade. To avoid the thermal bridge, PLUG-N-HARVEST project has developed a new aluminium profile that embedded thermal bridge breaker.

A combination of frame and layer-based system provides a continuous layer of insulation and frames for assembly of renewable modules. As illustrated in the top-right of figure 4 (BRESAER project), the combined approach enables a continuous layer insulation layer to be placed between the loading bear frame and existing facade. This can significantly reduce the contact area between the existing facade and the metal frame, but it still can't eliminate thermal bridge due to the metal brackets needed for fixing the frame thought the insulation layer.

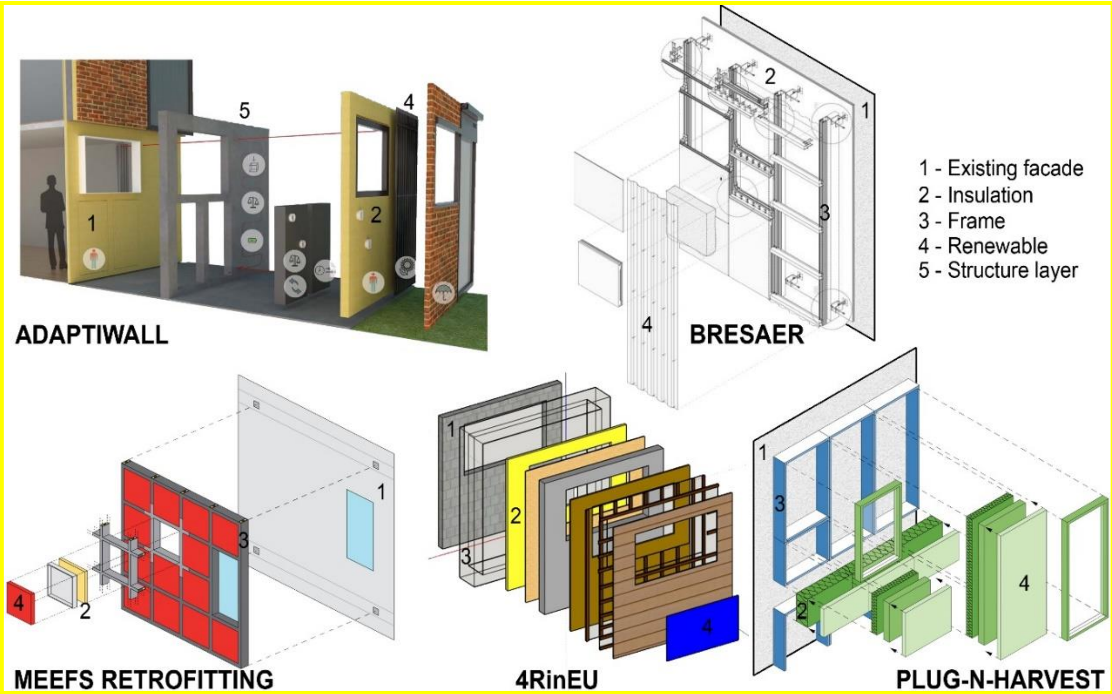

Figure 4 The design concepts of the typical MFRRn[2,5,7,9,10]

4.1.2 Integrated renewable technologies and passive components

The unique feature of MFRRn solution is that it enables modular assembly of renewable technologies and passive components such as windows, wall insulation, sun shading, and natural ventilation components. These modular passive components have been widely used in non-domestic buildings, particularly offices, hotels and student accommodations.

The design and selection of renewable technologies are often limited by the physical requirements and energy generation requirement. The physical requirements include orientation, weight, the depth of new façade, the dimension of frame grid, colour and texture of the outer layer. The energy generation requirement is decided based on local climate condition, energy demand, size of storage and energy management strategies. All projects in table 1 have considered one or more renewable technologies, such as Photovoltaics (PV), Building-integrated photovoltaics (BIPV), solar thermal, Building Integrated Photovoltaic/Thermal (BIPVT), as part of their modular facades. They can be classified into renewable heat generation, heat storage, renewable electricity generation and battery.

Building-integrated photovoltaics (BIPV) is the most popular solution that has been employed by a number of projects. They could be crystalline silicon PV or thin-film PV. The major difference is their weight, efficiency and mounting system. Thin-film PV is significantly lighter than crystalline silicon PV; however its production module efficiency is relatively low (in the range of 7-13%) comparing with the crystalline silicon PV's efficiency (13-20%). The mounting system for crystalline silicon PV has been industry standardised. Thin-film PV offers more flexibility in term of integration with frame and cladding.

The other notable Building-integrated renewable technologies include MEEFS RETROFITTING project's passive solar collector and ventilation unit. Their unit has a dual-layer where the external layer is semi-transparent and thermal storage wall is used as an internal layer for thermal storage. The lower and upper opening gaps on the external layer allow air exchange with the external environment. Its prototype has been tested, and the initial result shows that it can improve air quality and reduce domestic heating energy consumption by 20%-30%.

Smart management system for renewable technologies is another area of development. All projects in table 1 have considered building-level management system which is supported by wireless or cabled sensors and control algorithms. Some projects include EnergyMatching and PLUG-N-HARVEST projects also considered district-level energy demand response solutions together with renewable generation. Technological details of renewable technologies and smart management system will be reported in another review article.

4.2 Key players in MFRRn development and their contributions

In contrast to fundamental research, the development of MFRRn spreads from technology readiness level 1 up to level 9 and involves a large number of business partners. The traditional literature review method could not identify all critical players due to the timing (many of them are on-going research) and the fact that business partners often do not use academic journal articles as the channel to share the outcomes. Therefore, the authors decided to reveal the key players through the analysis on the engagements within the fourteen Framework 7 and the Horizon 2020 projects related to MFRRn development. These projects have involved 189 organisations from 29 countries with a total investment of nearly 100 million euro. Almost 80% of it is the funding from the European Commission, and the other 20% came from private match-funding.

An organisational network analysis was performed for the 14 projects and illustrated in figure 5. Each dot represents an organisation who participated in the fourteen projects related to MFRRn development. The size of the dot represents the funding values received from the European Commission. The colours and lines present the interactions within each project. If organisations involved more than one project, they are coloured in grey and labelled with a ranking in relation to the size of funding they have received.

It is noticeable that 17 organisations have participated in more than one projects. The Spanish research and innovation organisation Tecnalia ranked the top with total funding of 3.11 million euro and involvements of 6 projects. The Spanish infrastructure company Acciona and the Dutch research and innovation organisation TNO have both involved in 5 projects with around 3-million-euro support from the European Commission. The name, country, the number of projects involved and total funding for the 17 organisations are listed in table 3. It is clear that business and applied research organisation dominate the list. Public housing agencies and local authorities such as the Housing Agency of Catalonia, Oslo municipality and Madrid Municipal

Housing and Land Company also involved two projects due to their demonstration roles. The only university on the list is Israel Institute of Technology who participated in MEEFS RETROFTTING and BRESAER projects.

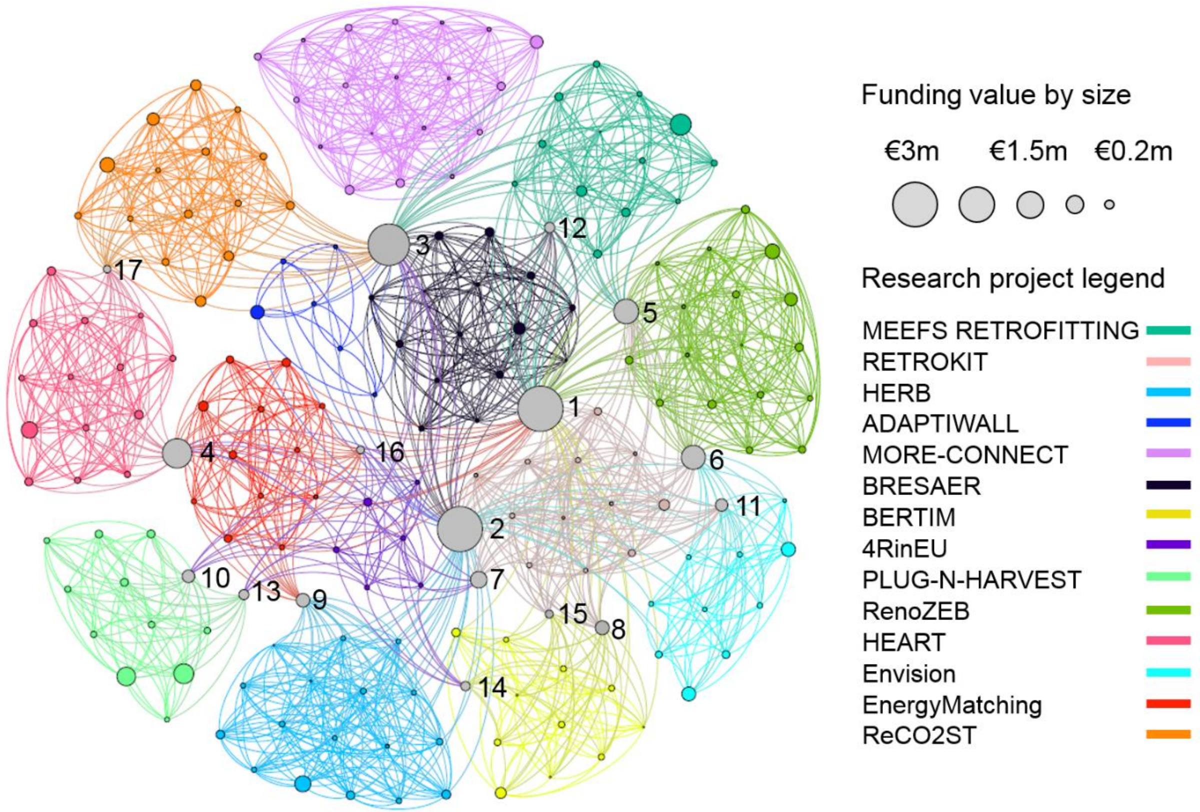

Figure 5 Organisational network analysis of project consortium related to MFRRn

Table 3 Organisations participated in more than one project related to MFRRn

Ranking	Institute name	Country	Projects	Funding
1	Fundacion Tecnalia Research & Innovation	Spain	6	€3.11M
2	Nederlandse Organisatie Voor Toegepast Natuurwetenschappelijk Onderzoek TNO	Netherlands	5	€3.10M
3	Acciona Construccion Sa	Spain	5	€2.84M
4	Accademia Europea Di Bolzano	Italy	3	€1.96M
5	Fraunhofer Gesellschaft Zur Foerderung Der Angewandten Forschung E.V.	Germany	3	€1.62M
6	Rina Consulting Spa	Italy	3	€1.57M
7	Stiftelsen Sintef	Norway	2	€1.03M
8	Rise Research Institutes of Sweden Ab	Sweden	2	€0.85M
9	Onyx Solar Energy S.L	Spain	2	€0.82M
10	Agencia De L'habitatge De Catalunya	Spain	2	€0.75M
11	Bergamo Tecnologie Spzoo	Poland	2	€0.73M
12	Technion - Israel Institute of Technology	Israel	2	€0.58M
13	Sistemes Avancats De Energia Solar Termica Sccl - Aiguasol	Spain	2	€0.56M
14	Oslo Kommune	Norway	2	€0.51M

15	Empresa Municipal De La Vivienda Y Suelo De Madrid Sa	Spain	2	€0.41M
16	R2m Solution Srl	Italy	2	€0.39M
17	Quantis	Switzerland	2	€0.38M

To track the involvement and funding flow to each country, the country-based statistic was also performed for the 14 projects. Figure 6 illustrates that Spain, Italy, Netherlands, France, Germany and the UK ranked top 6 respectively. Collectively they have shared over 53% of total funding resources. Due to the active engagement from Spanish research and innovation organisation Tecnalia, infrastructure company Acciona, renewable manufacturer Onyx Solar, public housing agencies at Catalonia and Madrid and many other organisations, Spain held the most substantial funding (16.8% of total) on the research involving MFRRn development.

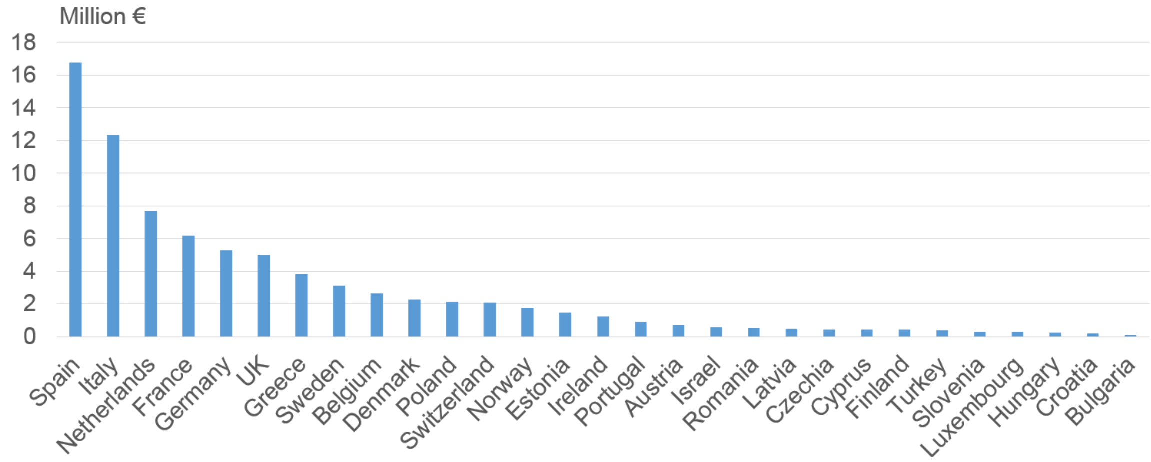

Figure 6 MFRRn development funding share by countries

Organisations may play different roles in different projects; therefore, it is challenging to detailed describe the specific activities and precise contributions that above 17 organisations have made during the project period. To understand the contributions to MFRRn development and which key players have made such contribution, all 189 organisations were ranked according to the funding they received from a single project. The top 10 organisations are listed in table 2. They all received more than 0.9-million-euro funding on a single project to advance certain aspects of the MFRRn development.

The Dutch research and innovation organisation TNO, Spanish infrastructure company Acciona and Spanish research and innovation organisation Tecnalia are on the list again due to their involvements on ADAPTIWALL, MEEFS RETROFITTING, BERTIM projects. The French thermoplastic pultrusion company CQFD Composites tops the list with the funding of 1.35m euro to develop a new industrialised pultrusion process for the structural frame within MEEFS RETROFITTING project. Research organisations such as RWTH Aachen University and the Fraunhofer Institute in Germany, Centre for Research & Technology in Greece, the University of Nottingham in the UK and Polytechnic University of Milan in Italy have played critical roles in many aspects of MFRRn development. Their project roles and main contribution/outputs to date (February 2019) are detailed in the last two columns in table 2. It is noticeable that most of them have taken on the crucial role of research development: project initiation and coordination.

Table 2 Top 10 organisations and their role in MFRRn development

No.	Institute name	Type	Country	Project name	Funding	Key role	Outputs at current stage
1	CQFD Composites Sarl	Private for-profit entities	France	MEEFS RETROFITTING	€1.35M	Reactive thermoplastic pultrusion structural panel design, assembling, testing, production and commercialisation	A new industrialised pultrusion process for cost-effective manufacturing of the structural components. A structural frame made of a thermoplastic composite material[2]
2	Rheinisch-Westfaelische Technische Hochschule Aachen	Higher education	Germany	PLUG-N-HARVEST	€1.26M	Modular, plug-n-play ADBE concept development. The installation at the demo site of the University.	An initial design concept [10]
3	Nederlandse Organisatie Voor Toegepast Natuurwetenschappelijk Onderzoek Tno	Research organisation	Netherlands	ADAPTIWALL	€1.19M	Project coordination. Research in building and civil engineering, mechatronics, mechanics, materials, earth, environmental and life sciences.	A conference paper about design an adaptive wall panel for retrofitting with multiple innovative technologies[79] A conference paper about design challenges based on simulations[80]
4	Ethniko Kentro Erevnas Kai Technologikis Anaptyxis	Research organisation	Greece	PLUG-N-HARVEST	€1.18M	Project coordination. Development of the PLUG-N-HARVEST Intelligent Management and Control System, Optimal Energy Management System at the district/grid level.	Secure and Intelligent Management of Near-Zero Energy Buildings[81]
5	Acciona Construccion Sa	Private for-profit entities	Spain	MEEFS RETROFITTING	€1.15M	Prototype development. Prototype testing. Pilot site demonstration.	An advanced passive solar protector and energy absorption unit. An installation Material Estimation Tool

							A structural module, compatible with the structural frame[2]
6	Politecnico Di Milano	Higher or Secondary Education Establishments	Italy	HEART	€1.02M	Scientific and Administrative Project Management. Integrated optimization of the whole system. Exploitation of the Project Results.	Ongoing development
7	The University of Nottingham	Higher or Secondary Education Establishments	United Kingdom	Heab	€1.00M	Develop models for optimisation of super insulation innovations in aerogel and vacuum insulated panel technologies. Develop an indoor environmental quality modelling methodology.	A journal paper about Cellulosic-crystals in vacuum insulated panel[82] A journal paper about retrofitting for energy and carbon saving[83] A conference paper about a new airtightness tester[84]
8	Fundacion Tecnalia Research & Innovation	Research Organisations	Spain	BERTIM	€0.95M	Project coordination. Prototype testing and pilot site demonstration. Provide prefabricated solutions and automated and digital tools for the optimisation	A conference paper about prefabricated solutions and automated and digital tools for the optimisation of a holistic Energy Refurbishment Process[85]
9	Solintel M&P Sl	Private for-profit entities	Spain	RenoZEB	€0.90M	Project coordination.	Ongoing development
10	Fraunhofer Gesellschaft Zur Foerderung Der Angewandten Forschung E.V.	Research Organisations	Germany	RETROKIT	€0.90M	Develop multifunctional framing elements.	Integrated façade elements[3]

5. Challenges and research focus

The implementation of advanced energy efficiency and renewable retrofit is facing a number of challenges. Simona *et al.*[86] reviewed 31 EU-funded projects that dealt with deep renovations and summarised the challenges from three aspects: technical challenges, financial challenges and social challenges. The deep renovations in their paper mean significant efficiency improvements with a reduction in energy in a range of 60-90%[87].

During the delivery of PLUG-N-HARVEST project, authors hosted workshops and interviews with key partners and identified the challenges for implementing MFRRn. These project-specific challenges are merged with lessons learned from the 14 projects listed in table 1. Comparing to deep renovations mentioned in Simona *et al.*[86]'s work, MFRRn includes on-site renewable energy technologies which often involve the complicated system integration. Therefore the unique challenges in MFRRn development and implementation are summarised in Table 4.

Table 4 Challenges in MFRRn development and implementation

Technical challenges	Financial challenges	Social challenges
• The concept is difficult to comply with building standards and updates. (e.g. Strict fire prevention requirements, historical building requirements, structural requirements.) • Existing buildings might have complex envelope conditions (e.g. large glazed area, overhang shading, downpipe, gutter, uneven wall surfaces, balcony and ventilation outlets). • Fast-changing renewable technologies and their limited lifespan comparing to buildings. • Healthcare, retail mall, storage building normally have their unique colour and textile specification due to branding or internal guidelines. • Integration of components and safe connection of cables, pipes are relatively complex. • On-site tolerance to be considered at the design stage.	• Transparency in new technologies and their availability in the local supply chain. • Relatively high cost due to renewable and energy storage system. • The up-front costs are higher than standard retrofitting. • The motivation to invest in MERRn is not clear for the general public. • Supporting schemes, such as government incentives, are not ready yet. • The retrofitting with renewable at small scale has a longer payback period comparing to large renewable development. • Extra work is needed for adapting an existing business model or developing a new business model.	• The trust in innovative technologies (and in general adapting for a change) is insufficient. • The traditional construction industry, large companies and clients don't have enough motivation and reluctant to changes. • Lack of understanding of the benefits (both social and financial benefits). • The information on the user behaviour, best practices and strategies for achieving comfort and saving energy are difficult to find. • Users in rental property often cannot provide the commitment in term of the care and maintenance for the MERRn. • The collective and individual needs might have a conflict. • Uncertainties in weather, usage pattern, maintenance could result in delay or

• Grid constraints and facilities shared energy.		failure during the implementation.

To systematically overcome the technical challenges, future research should focus on three elements of modular facade retrofit with renewable energy technologies: modular design and fixing methods, embeddable renewable technologies, and parts/technologies that are capable of coping with on-site tolerance.

The PLUG-N-HARVEST research team has gathered and compared local building regulations and requirements in different European countries for building retrofits. These include fire safety requirement, structural requirement, waste management, appearance, use of toxic and pollutants material, right of natural light, acoustic and ventilation. These regulatory requirements together with their legal updates form the foundation of modular design and fixing methods. The fixing methods are also the crucial aspect of modular design and have significant impacts on its assembly speed and structural status. Fast fixing methods should be systematically designed to cope with power wires, communication and control cables and services pipes that generally pass through or are attached on the facade.

The selection of embeddable renewable technologies and its decision-making tool are also crucial parts of ongoing development. This includes a screening process that firstly establishes a technique and their manufacturers' database; then a tailored integration design should be conducted together with the manufacturer. For example, the size of the PV panels and the location of the cable box should be redesigned according to the size of modular panels. For small size demonstrations, this involves typically bespoken design and manufacturing which could be expensive due to relevant certification and safety testing procedure. Due to the variety of renewable technologies, the different building energy demand profiles on heating, cooling and power depending on its usage and local climate, and most importantly the limited the size and orientation of facade, the optimisation process is needed to ensure energy generation maximised. Parameters building performance modelling could help achieve such task; however, it involves the development of energy models for each of renewable technologies. The interchangeable models for the latest technologies are always lagging behind the technologies themselves. A simple and user interface friendly parameters decision-making tool should be developed for modular façade retrofit.

One of the crucial advantages of off-site modular manufacturing is its precision; however, this could become its weakness when dealing with existing building retrofits, particularly low-rise domestic buildings. Building to be retrofitted are often over twenty years old, and they normally have uneven façade surface, non-horizontal floor and roof which could be challenging to manage if on-site tolerance was not considered at the designing stage. 3D laser point cloud scanning could help identify these features; however, it will involve relatively high survey costs. Besides, the panel and devices covering the facade will have an impact on the accuracy of 3D scanning. Therefore, parts/technologies that able to cope with on-site tolerance should be developed as part of modular design solutions. This often involves preparatory work on existing façade, the usages of the thermal insulation layer or bespoke measured parts to manage the tolerance, or the combination of above.

To overcome the financial challenges for any construction related technology including MFRRn, the transparency in technological and financial performance, and the availabilities in local supply chains are the essential information that designers, contractors and building owners needed for their decision making.

Within the European Commission's the seventh Framework and Horizon 2020 programme, a range of technologies and products have successfully increased their Technology Readiness Levels up to 5-8. However, this information might not be directly available to the public. Authors, therefore, developed the following three-layer organisational network analysis method (illustrated in figure 7) to bring unique products/services to the local supply chain and the end users. The top layer is Organisational Network Analysis (figure 5) using available public data from the European Commission's Community Research and Development Information Service which include project factsheets, participants, reports, deliverables and links to open-access publications. The second layer consists of the unique products/services that companies/ institutions have developed. Such information is not directly available, but they can be obtained through business review and market research. The third layer contains the geographical information about the products and services, such as the location of factories, supplier and expert agents. This three-layer analysis approach can dramatically increase the transparency in new technologies and map their availability in the local supply chain. New business opportunities and market penetration can then be achieved.

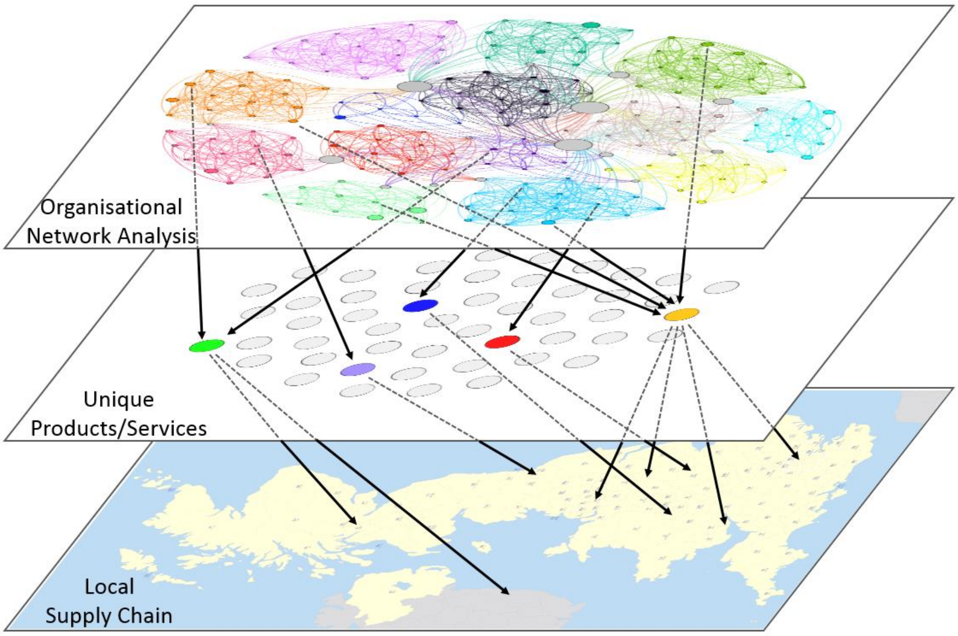

Figure 7 Three-layer organisational network analysis method

The recent study [88] shows that the increasing competitiveness of renewable electricity sources and the end of government subsidies are approaching. For example, the UK's Feed-In Tariff was introduced on 1 April 2010 and will end on 31 March 2019 for new applicants. Although the policy itself has a negative impact on the financial return of MFRRn, the business case still can be attracted by the decreasing capital cost of renewable technologies in next few years, which often are driven by technological innovation.

Social challenges in MFRRn development and implementation are often caused by the lack of understanding in products and its aftercare. Successful demonstration work and its publicity can increase its visibility and ensure the customer and investors to see its value and the advantages. A user-friendly online platform for introduction, training and aftercare of the

MFRRn and its subcomponents can also help customers accepting it quickly. Furthermore, the establishment of support and service warranty for MFRRn products should be a critical part of a business model to solve the problems after the construction. The involvement of insurance companies is an option to share the risk and maintain long-term stability in operation.

6. Conclusion

Although there are a growing number of academic articles and demonstration projects showcasing their achievements, the overview of current status and development trend are missing. As a part of the ongoing European Commission Horizon 2020 project team, the authors reviewed 173 research projects funded under the European Commission the seventh Framework, the Horizon 2020's Energy Efficient Buildings programme, the International Energy Agency Energy in Buildings and Communities (IEA EBC) Annex 50 'Prefab Systems for Low Energy/High Comfort Building Renewal' project, the European Cooperation in Science and Technology (COST) Action TU1403 'Adaptive facades network'. The review shows that at least 14 European Commission research projects and 4 case studies mentioned in COST TU1403 and IEA Annex 50 have involved in certain of level of MFRRn development. Their research progress, timeframe, funding scale and funding flow to nations and contributions from key institutes are analysed.

Due to the lack of clarification in previous studies, this article firstly utilised a modified ground theory (Confluence-refinement method) to introduce and define the term of Modular Facade Retrofit with Renewable energy technologies (MFRRn), then timely provided its classification and the review of recent evolution. According to our definition, the MFRRn should fulfil four basic aspects: work to be conducted on existing buildings, work to be undertaken on the facade, using a modular approach, and integrating renewable energy technologies during the retrofit.

This study highlighted the current technical, financial, social challenges and research focus regarding MFRRn development. Future research should focus on three technical elements of modular facade retrofit with renewable energy technologies: modular design and fixing methods, embeddable renewable technologies, and parts/technologies that are capable of coping with on-site tolerance. Designers, contractors and building owners needed more transparency in technological and financial performance and market penetration of MFRRn products through local supply chains. The establishment of support and service warranty for MFRRn products should also be an essential part of a business model to solve the problems after the construction.

Although this article limits its review within the scope of European Commission Horizon 2020 programme, IEA and COST Action, the experiences learned, challenges faced, and future research focus could be valuable to share with international audiences. For example, the Chinese National Key R&D Programme is also tackling modular retrofit and building integrated renewable energy technologies. International partner outside Europe, such as Israel Institute of Technology, actively participated in the development and dissemination of BRESAER and MEEFS RETROFITTING projects.

Authors admit that a new holistic approach has been carried to construct MFRRn concept and review the current status, this is due to the fact that there is no previous study to set up the boundary of the scope. There are tremendous studies on building integrated renewables for new buildings and some studies on modular facades for new buildings; however there are few studies on modular facades for retrofit and no journal article takes this holistic approach to review MFRRn. The authors' rigorous definition and precise classification should make further studies easier.

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Competing interests

The authors declare no competing interests.

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Contributions

H.D. and P.H. designed the study and led the writing of the paper. All authors have made substantial contributions to the classification and analysis of the modular facade retrofit technologies.

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Abbreviations

The following abbreviations are used in this manuscript:

BS	British Standards

BIPV	Building-Integrated Photovoltaics
BIPVT	Building-Integrated Photovoltaics and solar Thermal
BIST	Building-Integrated Solar Thermal
BIWT	Building-Integrated Wind Turbine
BSI	British Standards Institution
CORDIS	European Commission's Community Research and Development Information Service
EC	European Commission
EeB	Energy-efficient Buildings
EIA	Energy Information Administration
EU	European Union
FEMA	Federal Emergency Management Agency
IEA	International Energy Agency
ICT	Information and Communications Technology
ISO	International Organization for Standardization
MFR	Modular facade for retrofitting
MFRRn	Modular facade retrofit with renewable energy technologies
PCM	Phase-change material
PPP	Public-Private Partnership
PV	Photovoltaics

The following acronyms of European Commission supported projects are used in this manuscript. The full project names are listed below:

4RinEU	Robust and Reliable technology concepts and business models for triggering deep Renovation of Residential buildings in EU
A2PBEER	Affordable and Adaptable Public Buildings through Energy Efficient Retrofitting
ADAPTIWALL	Multi-functional light-weight WALL panel based on ADAPTive Insulation and nanomaterials for energy efficient buildings
BERTIM	Building energy renovation through timber prefabricated modules
BRESAER	Breakthrough solutions for adaptable envelopes for building refurbishment
BuildHEAT	Standardised approaches and products for the systemic retrofit of residential Buildings, focusing on HEATing and cooling consumptions attenuation.
E2VENT	Energy Efficient Ventilated Façades for Optimal Adaptability and Heat Exchange enabling low energy architectural concepts for the refurbishment of existing buildings
EASEE	Envelope Approach to improve Sustainability and Energy efficiency in Existing multi-storey multi-owner residential buildings
EENSULATE	Development of innovative lightweight and highly insulating energy efficient components and associated enabling materials for cost-effective retrofitting and new construction of curtain wall facades

EnergyMatching	Adaptable and adaptive RES envelope solutions to maximise energy harvesting and optimize EU building and district load matching
Envision	ENergy harVesting by Invisible Solar IntegratiON in building skins
HEART	Holistic Energy and Architectural Retrofit Toolkit
Heat4Cool	Smart building retrofitting complemented by solar assisted heat pumps integrated within a self-correcting intelligent building energy management system.
HERB	Holistic energy-efficient retrofitting of residential buildings
MEEFS RETROFITTING	Multifunctional Energy Efficient Façade System for Building Retrofitting
MF-RETROFIT	Multifunctional facades of reduced thickness for fast and cost-effective retrofitting
MORE-CONNECT	Development and advanced prefabrication of innovative, multifunctional building envelope elements for MOdular REtrofitting and CONNECTions
PLUG-N-HARVEST	PLUG-N-play passive and active multi-modal energy HARVESTing systems, circular economy by design, with high replicability for self-sufficient districts near-zero buildings
Pro-GET-OnE	Proactive synergy of inteGrated Efficient Technologies on buildings' Envelopes
ReCO2ST	Residential Retrofit assessment platform and demonstrations for near zero energy and CO_2 emissions with optimum cost, health, comfort and environmental quality.
REnnovates	Flexibility Activated Zero Energy Districts
RenoZEB	Accelerating Energy renovation solution for Zero Energy buildings and Neighbourhoods
RETROKIT	RetroKit - Toolboxes for systemic retrofitting

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