# Circularity concepts for offsite prefabricated energy renovation of apartment buildings

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**Abstract.** Deep energy renovation includes the realisation of the full potential of energy performance. A circular deep renovation, which contributes to a circular built environment, is based on 100% life cycle renewable energy, and all materials used within the system boundaries are part of infinite technical or biological cycles with the lowest quality loss as possible. In the current study, the circularity potential was assessed for deep energy renovation from different aspects: circularity of materials, building component and building structure. Careful selection of materials as well as connection, position and disassembly possibilities are needed to increase the degree of circularity. This shows a good possibility to increase energy performance by using circularity principles. The window glass circularity analyse showed that, at best, the thermal transmittance of a new circular product can be more than three times lower than the original. The circular use of materials, components, and structures pose new challenges for the building physic design of building envelope structures.

## 1. Introduction

Half of the Earth's raw materials are used for construction. Construction Products Regulation [1] seeks to ensure reliable information on the performance of construction products. Although primarily related to operational quality, one of the basic requirements for construction work is the sustainable use of natural resources. The construction works must be designed, built, and demolished in such a way that the use of natural resources is sustainable and in particular ensure the following:

- reuse or recyclability of construction works, their materials, and parts after demolition;
- durability of construction works;
- use of environmentally compatible raw and secondary materials in construction works.

Ecorys estimated in their analyse of resource efficiency in the building sector, hat embodied energy in building products was around 1.9 Million TJ in 2011 [2]. The embodied energy of the produced building materials account 11 – 15% of the total energy used by residential buildings. The embodied energy in building products make up 20% of the EU27 industry's final energy consumption.

Directive on waste [3] sets the basic concepts and definitions related to waste management, such as definitions of waste, recycling, recovery. This concerns also, among others, construction and demolition waste (CDW). To comply with the objectives of this Directive and move towards a European recycling society with a high level of resource efficiency, Member States shall reuse, recycling and material recovery a minimum of 70 % by weight.

The European Commission has published its Renovation Wave Strategy [4]. To improve the energy performance of buildings, at least the renovation rates should double in the next ten years. This causes an increasing use of natural resources to produce materials for renovation. By 2050 in Estonia, up to 10 M square metres of apartment buildings and nonresidential buildings will fall out of use. This causes an increasing of CDW. The demolition and destruction of buildings instead of the reuse or recycling of materials leads to a loss of material.

The increasing use of natural resources and the associated environmental impact are a serious threat to the EU's natural, social and economic system. Overcoming this challenge requires both renewable energy technology and the reuse and recycling of resources / materials. Therefore, a deep and circular renovation of buildings is needed across Europe to address the decarbonisation of the built environment [5]. A good (circular) design means making choices on which concept and on which strategies to deploy. Furthermore, designing with future disassembly and reuse in mind and promoting commitment among clients and other stakeholders can further help accomplishing circular applications within the built environment. Current study analyses the circular renovation possibilities of prefabricated insulation elements for offsite energy renovation.

## 2. Methods

### *2.1. Circularity and potential for circularity*

In H2020 project DRIVE0 [5] developed a method [6] for benchmarking of renovation circularity was used in the current study, see Table 1.

**Table 1.** Level 1 (left) and Level 2 (right) circularity assessment.

| **Circularity and potential for circularity** | |
|---|---|
| The level 1 assessment<br>• General questions,<br>• Questions related to a material as a product,<br>• Questions related to a product,<br>• Questions relevant to multifunctional products. | Level 2 circularity assessment<br>• Estimation of service life, years<br>• Mass of materials, kg/m² (floor area)<br>• Embodied Energy of materials, MJ/m²<br>• Embodied $CO_2$ of materials, kg/m²<br>• Material division: new, reused and recycled |
| **Design for disassembly** [7]<br>• Type of connections,<br>• Accessibility of connections,<br>• Crossings,<br>• Form containment,<br>• Material selection. | **Material selection**<br>• Locally repaired, reused building components and materials<br>• Biobased materials<br>• Recycled, upcycled components, materials<br>• Refurbished, remanufactured materials |

### *2.2. Case study building*

Estonian pilot building in H2020 project DRIVE0 was used for benchmarking of circular renovation possibilities. The building is a 3-story apartment building with 24 apartments, a total area of 2415 m², built in 1986 (Figure 1). This building type was widely built in the 1970s-90s.

**Figure 1.** Photo of the case study building before (left) and during (right) the renovation.

Load bearing walls are made from aerated autoclaved concrete (AAC) panels. The roof was replaced approximately 10 years ago and most of the apartment owners have replaced old wooden windows with PVC windows. Building service systems are not renovated. Ventilation system is a natural passive stack ventilation (separate ventilation shaft for every apartment). Heating system is a one-pipe hydronic radiator system with district heating as a heat source for space heating and the heating of domestic hot water. The building is to be renovated using prefabricated timber frame insulation elements [8] and the circular renovation concept

## 3. Results and discussion

### *3.1. Potential for circularity on the material level*

The circular use of materials is described on four different levels:

- added reused, recycled, biobased, materials to the renovated building (Table 2);
- the reuse of existing materials from the renovated building in the renovated building (Table 3);
- the reuse of existing materials from the renovated building in another building (Table 4),
- recycling of existing materials from the renovated building.

**Table 2.** Added materials to the renovated building.

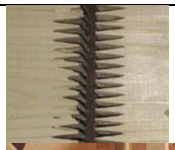
| Material | Description of circularity | |
|---|---|---|
| Timber frame in insulation element | Recycled material<br>Use of finger joists when making timber for insulation elements. Due to the facade boarding cross-framing is also required. Finger joists timber could be also cheaper. |  |
| Insulation on attic floor | Recycled material.<br>Blown wool insulation from glass wool or cellulose insulation. The use of cellulose insulation may be restricted by fire safety regulations. For producing glass wool products can be use up to 80% recycled glass. As this becomes high-quality glass 'cullet', it enables us not only to save virgin raw materials but can also reduce energy use by up to 20%. |  |
| Façade boarding | Biobased material.Wooden boarding external walls of stairwells (long roof overhang) and balcony border. Boarding of the external wall of a 3-8 storey building may be made of D-$s_2$, $d_2$ flammable material, if the insulation material meets at least $A_2$ requirements. The fire sensitivity of the wind barrier and ventilating air gap of an up to eight-storey building a must be from D class if the structure surrounding this part prevents the spread of fire on the wall surface and the insulation material meets at least $A_2$ class. |  |
| Wood fiber wind barrier | Biobased material.<br>The possibility to use depends on fire safety regulations (see above). Can be used if there is a fire barrier membrane in the ventilation gap. |  |
| Textile based wind barrier or insulation | Recycled material<br>Many products on the market or under development. Can be used if certified material is in the market ($A_2$). Also locally products exists but today without product declaration nor certificate. |  |

**Table 3.** Reuse of existing materials from the renovated building in the renovated building.

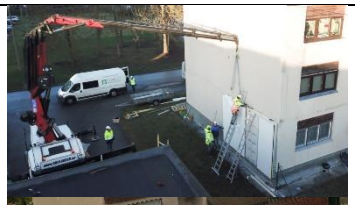
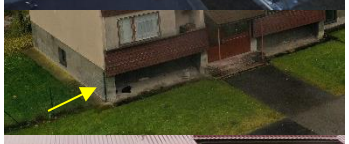
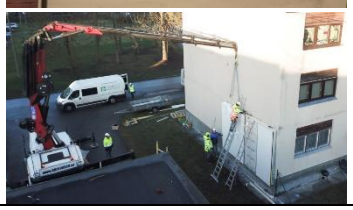
| Material | Description of circularity | |
|---|---|---|
| Dissembling of insulation element | When the hygrothermal measurement period for the wall prototype ends, we will disassemble the elements and show that we will use them for making of new elements. |  |
| Plinth paving (concrete) | New concrete from old concrete. Not for load bearing structures. Reinforcement cannot be used as it must be inspected and certified. |  |
| Wooden boarding above the windows and on the balcony. | We document the material's condition before disassembling:<br>• how much material can be recovered?<br>• how much does need cleaning, priming, painting?<br>• what will be the cost? |  |
| Old radiators | Reuse of old radiators in the stairwell. They are not used elsewhere because there are not enough radiators that are technically in order. Radiators must be cleaned, repaired, and repainted. |  |
| Old service systems | Heating and water pipes are expected to be clogged. They will be use for bicycle stand. Pipes must be cleaned and repainted.<br>We will not of electric cables reuse for safety reasons. Some old sockets, old switches, the old luminaire could be retained. |  |

**Table 4.** Reuse of materials from the renovated building in another buildings

| Material | Description | |
|---|---|---|
| Roof's covering (metal sheet) | The roof covering (metal sheet) will be used for roof of another building. |  |
| Old windows | Removing windows with different technology. What are the different sizes of glasses? Is it possible to add a third glass to a double pane glass? Balcony glass (+ safety glass). Greenhouse for urban garden is possibility to reuse of old material in a new function |  |
| Dissembling of insulation element | On the panels to be installed, we will demonstrate the potential for disassembly after 50 – 70 years. It will be possible to demount of insulation elements and use them to construct a terraced house. |  |

### *3.2. Façade insulation element*

The assessment on product level has been done for the prefabricated façade insulation element. Cross section and the connections of the façade element are shown in **Figure 2** and **Figure 3**.

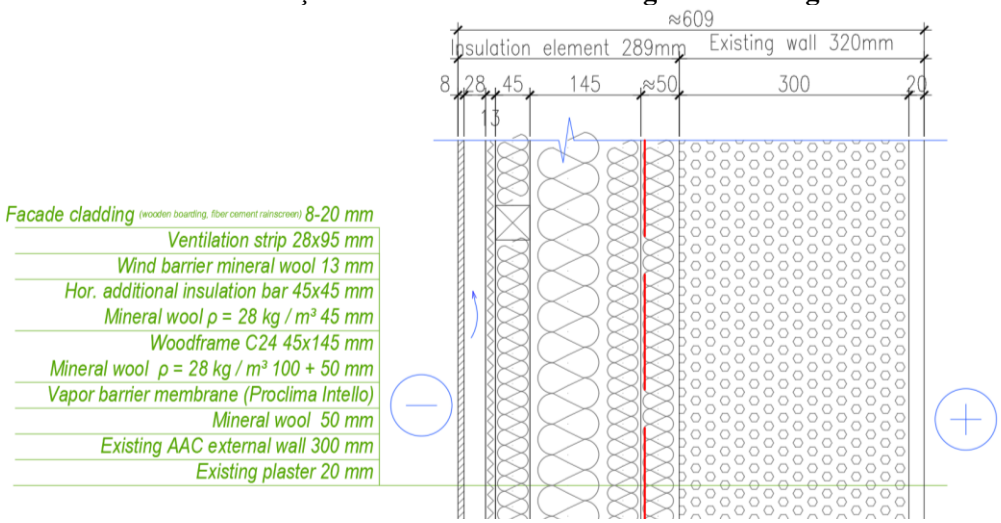



**Figure 2** Cross section of façade insulation element.

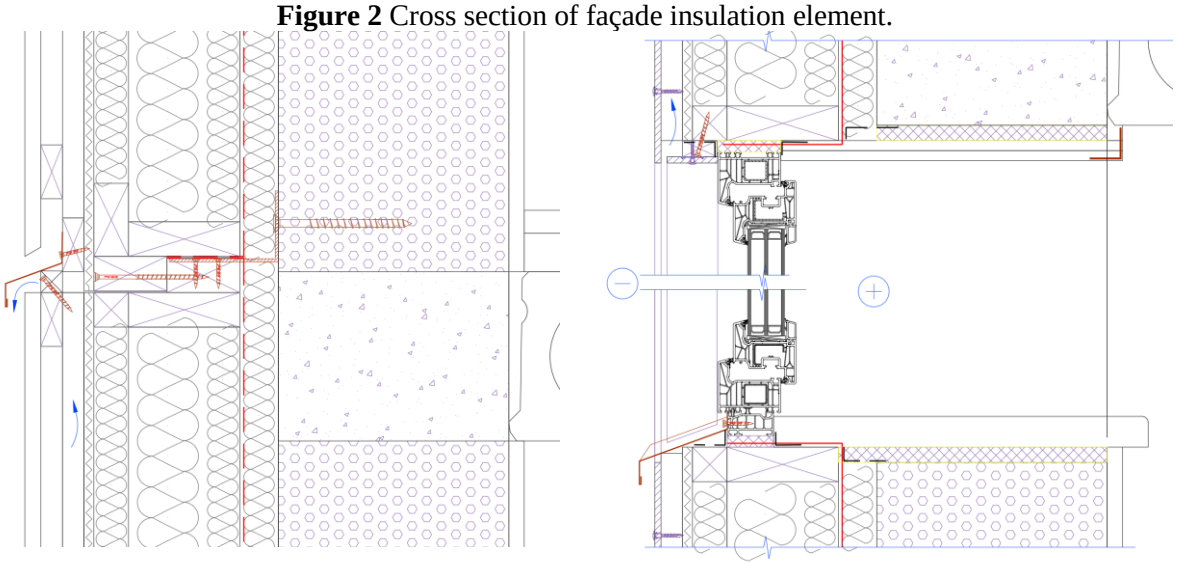


**Figure 3** Vertical connection of two facade insulation elements (left) and external wall and window (right).

On a product level a medium degree of circularity has been achieved (Table 5). Type and accessibility of connections, crossings and form containment showed high degree of circularity (>0.8) and material use showed low degree of circularity (<0.6).

Used insulation, wind barrier, and façade cladding materials are not biobased nor reused. Stone wool the insulation is used in insulation element because it is easier to handle and creates less fibre dust in factory conditions. Glass mineral wool would also have a higher material re-use score because 50%...80% of the material used for production is recycled glass. Insulation element with cellulose insulation would achieve a higher score, but cellulose insulation cannot be used because of the fire safety regulations. The case study building is a TP1 class building with 3 floors which requires that the insulation must have at least fire resistance class $A_2$. Cellulose wool has fire resistance class B1. Decreasing of fire safety from TP1 to TP2 is possible in principle according to the fire safety regulations

The goal of using materials with a smaller environmental footprint may mean using new materials. Hygrothermal properties of materials should be well known, because the building envelope of the future nZEB needs a careful hygrothermal design [9].

**Table 5** Circularity assessment of façade insulation element.

| | Element (n) | Type of Connection | | Accessibility of connection | | Crossings | | Form containment | | Materials | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Connection to existing wall | Corner and screw | 0.8 | No damage | 0.8 | Modular zoning | 1.0 | Overlaps on one side | 0.8 | - | |
| 2 | Buffer insulation (glass wool) | Screw and line | 0.8 | No damage | 0.8 | Modular zoning | 1.0 | Open, no inclusions | 1.0 | Recycled material | 0.6 |
| 3 | Timber framing | Screw | 0.8 | No damage | 0.8 | Modular zoning | 1.0 | Open, no inclusions | 1.0 | Biobased material | 0.8 |
| 4 | Insulation (stone wool) | Dry | 1.0 | No damage | 0.8 | Modular zoning | 1.0 | Open, no inclusions | 1.0 | Mainly virgin material | 0.1 |
| 5 | Wind barrier (stone wool) | Screw | 0.8 | No damage | 0.8 | Modular zoning | 1.0 | Open, no inclusions | 1.0 | Mainly virgin material | 0.1 |
| 6 | Wooden lath | Screw | 0.8 | No damage | 0.8 | | | Open, no inclusions | 1.0 | Biobased material | 0.8 |
| 7 | Facade cladding (fibre cement) | Screw and EPDM seal | 0.8 | Freely accessible | 1.0 | Modular zoning | 1.0 | Open, no inclusions | 1.0 | Mainly virgin material | 0.1 |
| Category average | | | 0.83 | | 0.83 | | 1.0 | | 0.83 | | 0.42 |
| Circularity index | | 0.78 | | Medium degree of circularity | | | | | | | |

*3.3. Window*

Renovating windows and walls performs environmentally significantly better than only renovating windows or walls [10]. Therefore, the second building component that was analysed from the circularity point of view is window. Thermal transmittance of old windows of not renovated apartment buildings is in the range of 3 to 1.8 W/(m²K) [11]. To fulfil nowadays renovation suggestions [12,13] and renovation grant requirements, thermal transmittance of windows should be ≤1.1 W/(m²K). Changing of the old window to a new window with *U* 1.1 W/(m²K) gives the lowest life cycle cost and a longer technical lifetime, even no other energy efficient measures are implemented [14]. Even the cost of thermal transmittance is high, window has one of the most cost-effective measure to improve the energy performance because it's cost to change the unit of energy performance value €/(kWh/(m² ·a)) is the lowest [15]. To avoid the critical thermal bridge in the connection of the external wall and window, window should locate on the insulation layer [16].

In a common energy renovation, the improvement of window is not very circular today. Windows are replaced with new ones and old windows often end up on landfill or in the better case goes to recycling: glass to remelting or for raw material for glass wool. Both are very energy intensive processes and require transportation far from the factory.

This study presents a solution to increase the circularity of windows by producing a 4-pane glass window from an old 2-pane glass window, Figure 4. From old windows it is necessary to remove the 2-pane glass packages, clean and wash them and combine the two 2-pane glass packages into 4-pane glass package. This requires that the old 2-pane glass packages are the same size. This is very probable to achieve as for one apartment windows are ordered usually with the same size.

New frame is needed for 60 mm – 66 mm thick 4-pane glass window. For this, it is possible to produce a completely new frame (from wood or recycled PVC) or to modify the existing wooden frame (typical thickness 90 ± 2mm). Regarding the framing materials, wood has the lowest embodied impacts, while aluminum frame has the highest [17].

Ideally, there is an old glass package with low emission glass toward inside the pane. To improve the energy performance of 4-pane glass is possible to increase by installing an additional low-e film, that is made by depositing thin metallic and proprietary coatings on a flexible adhesive film substrate. The production of new 4-glass from the old two double-glazed units has the potential to reduce the thermal transmittance by about 2.7 to 3.4 times. This shows a good possibility to increase the energy performance by using circularity principles. The mass effect should make the process cost effective.

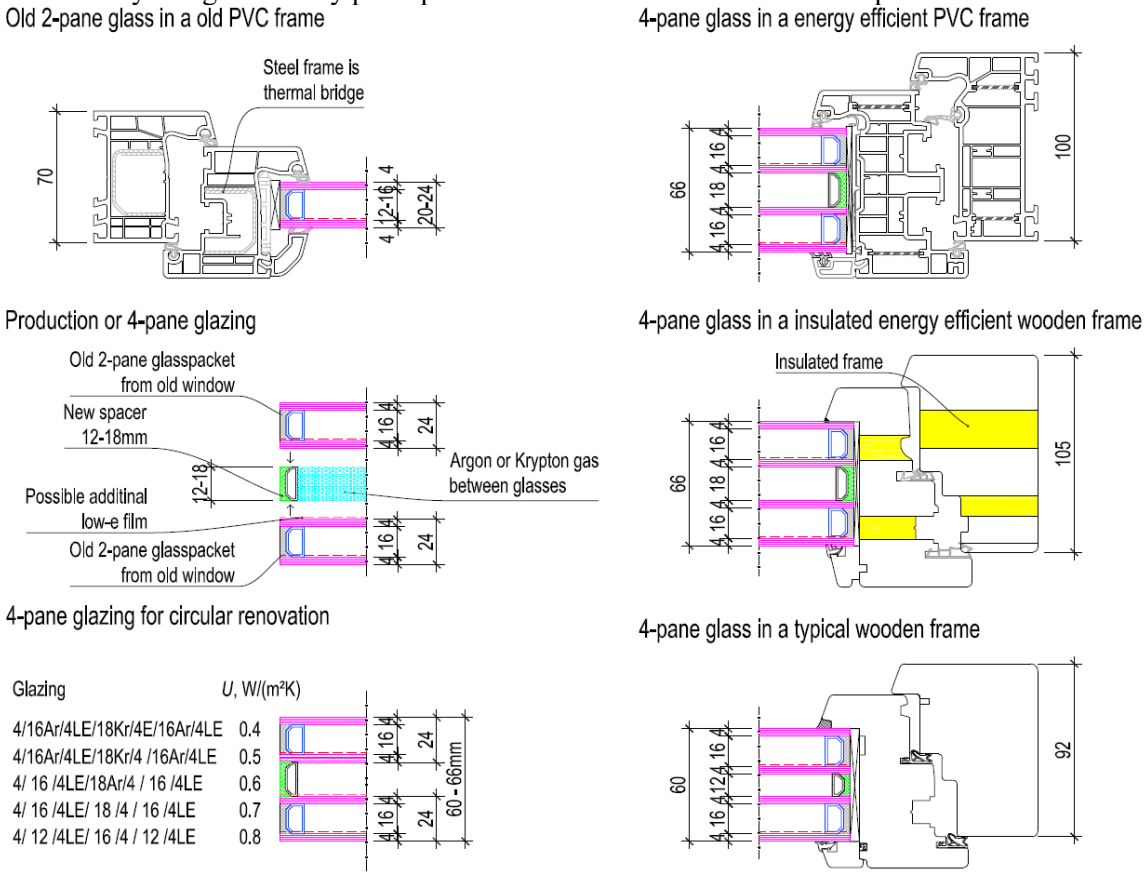



**Figure 4** Principle of production a 4-pane glass window from old 2-pane glass window to increase the renovation circularity.

## 4. Concussions

The renovations wave ahead of us requires a holistic approach to the development of renovation solutions. The cost-effectiveness of solutions alone is no longer the only evaluation criterion.

This study analyses circularity concepts (on TRL levels 2-3) for offsite prefabricated energy renovation of apartment buildings from different aspects of circularity:

- materials (added materials to the renovated building, reuse of existing materials from renovated building in the renovated building, reuse of existing materials from renovated building in other building, recycling of existing materials from the renovated building;
- building component, window as an example;
- building structure, prefabricated insulation element for the external wall as an example.

Although the essential requirements for construction include the requirement for the sustainable use of natural resources, circularity is not yet a common practice in everyday design. In the near future circularity (on the material level, component level and structural level) will be part of the designer's task. When circulation becomes part of a conventional design, it adds the whole process to one variable. For repaired, reused, recycled, refurbished, remanufactured materials, it is also necessary to declare hygrothermal material property in order to ensure the moisture safety of the building.

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