Upscaling the housing renovation market through far-reaching industrialization

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Upscaling the housing renovation market through far-reaching industrialization

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Abstract. The European existing building stock contributes to 40% of the total energy use and 36% of the CO_2 emissions. To deal with the climate crisis, European climate and energy objectives were defined. By 2050, CO_2 emissions should be cut to 80-95% compared to 1990 and all buildings must be energy-neutral. The North-Sea Region alone consists of 22 million outdated dwellings built between 1950 and 1985 that are in high need of renovation. Nowadays, the renovation industry applies mainly manual on-site renovation techniques, resulting in a low renovation pace, relatively high labour costs and a long duration. To tackle the urgent need for rapid renovations, six countries of the North-Sea Region collaborate to upscale the current renovation process in the Interreg project INDU-ZERO "Industrialization of house renovations toward energy-neutral". The project focuses on modular prefabricated renovation packages with fully integrated HVAC technologies to arrive at energy-neutral dwellings. The project researches the possibilities of far-reaching automated and industrialized production processes. A smart factory blueprint will be designed to speed up the renovation pace to a target of 15,000 renovation packages per year per factory while cutting the current price with 50%. This contribution focusses on three main topics: material use, operational energy use and transport. Firstly, the reasoning behind the renovation package design is explained. Next, the packages are adopted on an archetype dwelling to document the thermal performance before and after renovation. Finally, the associated logistics are studied. To summarize each individual research in a blanket result, the environmental impact is determined and compared to the non-renovated dwelling.

1. Introduction

The North-Sea Region (NSR) contains 22 million dwellings built between 1950 and 1985 causing 79 Mton CO_2 emissions annually. Current home renovations are being carried out on a limited-scale and many dwellings are not deeply renovated, resulting in a low renovation pace due to phased on-site works and weather dependence, relatively high labour costs and buildings that continue emitting CO_2. With current means, the targets of the Paris Agreement, the European Long Term Strategy and the ambitions of the European Green Deal will not be attained.

To tackle the urgent need for rapid renovations, six countries of the NSR collaborate in the Interreg NSR project INDU-ZERO "Industrialization of house renovations toward energy-neutral" with the ambition to upscale the current renovation process and to create the necessary facilities. INDU-ZERO aims to design a factory blueprint based on Smart Industry and Circular Economy to produce 15,000 fully integrated prefabricated renovation packages per year per factory suitable for all NSR countries at a reduced cost of 50%. The design of the packages is aimed to achieve energy-neutral dwellings in one-step. The project definition of energy-neutral implies that the energy demand is fully compensated by renewables on an annual basis. The energy demand for household appliances, lighting, material extraction, production and distribution are not included.

As a future perspective, the blueprint can support lead investors, building material groups, housing owner associations, governments and public authorities to invest in factory developments. This could improve the NSR economies and building sector by opening a market for deep renovation packages and lead to sustainable and energy self-sufficient dwellings in all NSR countries that meet the 2050 targets.

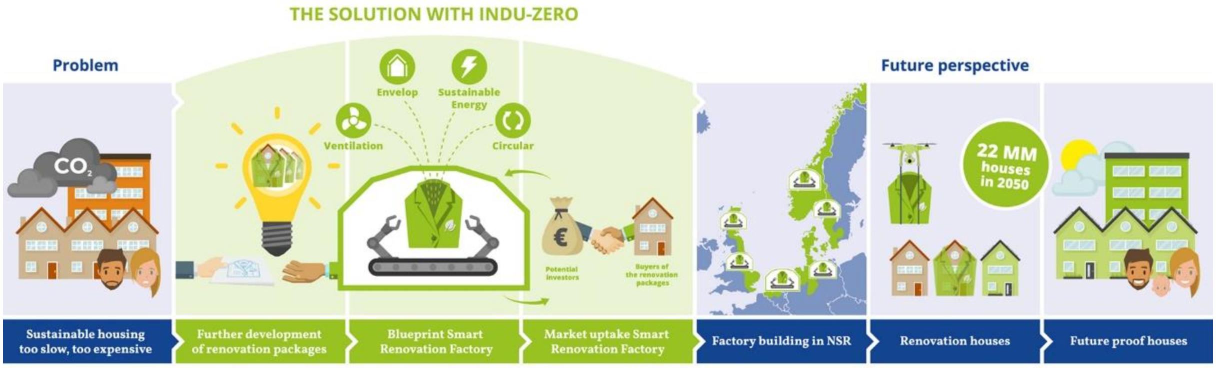

Figure 1. Infographic of the NSR project INDU-ZERO

2. Renovation packages: development and composition

2.1. *Methodology*

The renovation packages are developed considering several design boundaries related to the aims of the project such as the production speed, the impact on CO_2 reduction and the total cost of ownership.

Firstly, the renovation packages must be independent of a specific project. This, compared to the conventional way, eliminates the on-site complexities and constructability issues. Stripping down the dependencies to a bare minimum is done through placing the renovation packages as a coat over the existing building. In this way, the necessary variations are limited to the location of windows, the load-bearing capacity and the dimensions of the dwelling. These variations are measured on site by 3D scanning to guarantee the dimensional and surface accuracy. Moreover, limiting the variations in the design process enables repeatability and a mass production manufacturing approach to produce big amounts of renovation package components in short time.

Secondly, the renovation packages have to be pre-assembled as much as possible in order to cut down the labour time, the total costs and the nuisance on site.

Lastly, to improve the total life-cycle cost and the initial investment cost, an integrated design philosophy is crucial. The wall and roof components need to be fully integrated with heating, ventilation and energy generation through for example photovoltaic (PV) modules. Careful consideration must be given to the materials used for each element to lower the costs together with the environmental impact.

2.2. *The wall component*

Sandwich panels are preferred for the wall component because of their simple structure with few different constituting parts compared to wooden and metal frame panels. The panel consists of an 18 cm thick expanded polystyrene layer sealed with a thin polyester layer to enhance the strength and air tightness of the panel. On top of these layers, cladding is glued such as stone strips, wood finishing or stucco. Figure 2 represents the assembly of the sandwich panel. Frameless triple glazing is off-site integrated in the sandwich panel together with the decentralised units (DCU) locally providing the required ventilation and heating need.

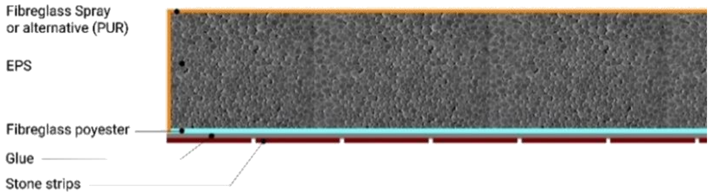

Figure 2. Assembly of the wall component design: sandwich panel

2.3. *The roof component*

For the same reason as wall component, sandwich panels are favoured over other structures for the roof component. The roof panels have the same assembly as the wall except that they are fully covered with PV panels. This way of building-integrated PV mounting on a factory floor demands a new way of connecting elements, construction mounting and load bearing.

3. Energy performance before and after renovation

The project INDU-ZERO focuses on three archetypical dwelling types: apartments, terraced and semi-detached dwellings built between 1946 and 1974, which collectively represent 30% of the existing housing stock (52 million) in the countries forming the NSR.

To determine the impact of applying renovation components on environmental a representative Dutch terraced dwelling has been chosen [1,2], see **Fout! Verwijzingsbron niet gevonden.**.

Figure 3. Representative dwelling, type terraced dwelling

The typical terraced dwelling for 3 occupants comprises 5 rooms over 2 storeys with 106 m^2 net floor area. The dwelling is poorly insulted with 60% of the fenestration being double-glazed. The other share is single-glazed. The dwelling is naturally ventilated and equipped with a gas boiler. The thermal transmittance (U-value) of the external walls and roof are 1.67 and 1 W/m^2K, respectively. To determine the impact of the renovation packages on the energy performance of the terraced dwelling, the Passive House Planning Package (PHPP) has been used. PHPP is a building energy calculation tool, which has been developed to assist architects and engineers in developing concepts for low-energy buildings. The PHPP calculation tool initiates a series of monthly state energy balance calculations according to EN ISO 13790 [3]. The impact of adding insulation and increasing airtightness has a significant effect on the annual energy demand for heating of the terraced dwelling. The calculations show a reduction of 31% by improving the U-value for external walls and roofs to 0.18 and 0.17 W/m^2K, respectively. Taking into account a reduced heat loss (50%) by infiltration after completion of the renovation reduces the annual energy demand for heating to 101 kWh/m^2, which corresponds to a reduction of 41%.

4. Logistics for large scale industrial manufacturing

Industrial mass production is not only based on the precise timing of manufacturing machines to the split second, but also on the required and optimally coordinated supply chain management. It is crucial to be always informed about all raw materials and products, inventories and purchase times along the supply chain in order to be able to influence them at any time to avoid production stops. However, in

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the digital age of Industry 4.0, logistics is more than just the right product, in the right quantity and the right condition, to the right place at the right time for the right customer at the right price. [4] An intelligent supply chain and its self-controlling transport management system are already able to take over many tasks of a Smart Factory in advance with regard to procure the needed information for incoming trucks as well as planning the loading ramp utilization, the automation of internal goods flows and the warehouse. Thus, the Smart Factory can more focus on the timing of the production of their own goods, since all boundary conditions related to logistics are already taken over by the smart supply chain management. This ultimately enables a faster production. [5]

INDU-ZERO serves as an example for the design of a Smart Factory and its intelligent supply chain, as the future daily handling of all arriving and departing trucks, including their transport and route planning, are already considered during the design of the blueprint, to make them as efficiently as possible and sustainable. The transport distances from the suppliers of the individual building materials to the Smart Factory and subsequent from the factory to the construction sites play a decisive role, as considerable CO_2 emissions also occur during the transport. In contrast to the conventional production of individual building materials and their use in house renovation, INDU-ZERO requires a further step in the supply chain. Normally, raw materials (e.g. clay) are brought to the producers for insulation or building materials (e.g. bricks) and after further processing directly to the construction site, where they are finally used for building or renovating a house. However, in the case of INDU-ZERO, the produced bricks first have to be brought to the Smart Factory, where they are integrated into the renovation packages. Afterwards, the transport to the construction site takes place. Accordingly, it is necessary to offset the here caused CO_2 emissions somewhere else.

In order to minimize this obstacle, a reasonable location planning is indispensable for the Smart Factory. The analysis includes all information regarding position, accessibility and transport connections of the location, catchment area for the customers, proximity to suppliers, security of supply, quality of the available locations as well as competition. Since the supplier locations have already been identified, the future factory can be located in their vicinity to avoid long transport distances. On average, the transport distance from the suppliers to the manufacturers of the products in the European construction industry is 130 kilometres per route, as fFigure 4 illustrates. This number resulted from quantitative research in which the production sites of the largest European building companies were compared with the nearest seaport by means of a statistical generalization. It was assumed that construction companies import a large part of their iron and steel production goods from there.

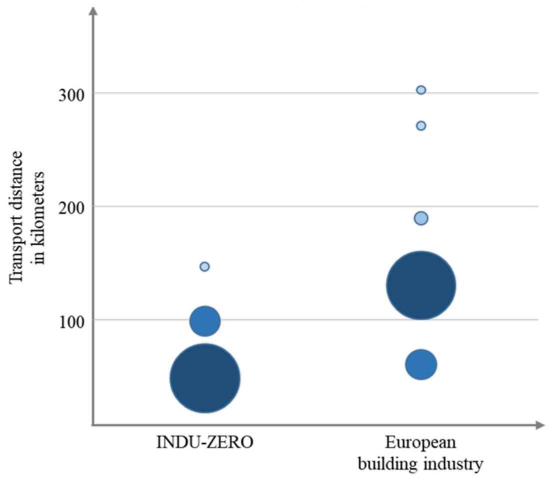

Figure 4. Transport distance from suppliers to producers in the building industry

Due to the location planning, the average transport distance can be reduced to around 60 km per route in INDU-ZERO. This results in annual transport savings of over 4 Mton of CO2. In the end, it balances the fact that there is one additional transport along the supply chain compared to conventional systems. Furthermore, only Euro 6 trucks with maximum capacity utilization are used for transporting raw materials and products in order to keep CO_2 emissions per tonne as low as possible and to transport the largest transport volume at the same time. The use of various transport vehicles, such as delivery vans or heavy transporter, has been tested and is not an option due to the low transport capacities, as roughly 90 trucks per day are needed to achieve the target of 15,000 refurbishment packages per year. These dimensions cannot be realized by delivery vans. Moreover, due to legal regulations, no heavy transporters will be used for carriage. Currently, a system is established how empty truck return trips can be avoided. The aim is to also use the trucks responsible for the delivery of the individual building materials for the transport of the refurbishment packages to the construction sites near of their suppliers. The new transport methods would approximately result in a round trip with over 80 % full-utilization of the trucks, which is 20 % higher than the European comparison [6]. At the end of the day, it is not only decisive how much CO_2 can be saved by transport, but also how many resources and energy are spent in the production, usage and disposal of a product. Considering the total ecological backpack, the next section will investigate whether are not the adoption of the renovation packages on the reference case described in §2 still results in a final CO_2 reduction.

5. Environmental impact of the renovation packages

5.1. *Methodology*

In this part the environmental impact to renovate the terraced dwelling described in §3 with the renovation packages elaborated in §2 will be evaluated taking into account the lowered operational energy use and the energy needed for producing and transporting the renovation packages to the building site. This is done through a life-cycle assessment (LCA) assuming a total lifespan of 60 years.

The LCA analysis is performed using SimaPro v9.0.0.49. The Swiss Ecoinvent database v3.5 is selected as the life cycle inventory database containing all required input flows that fit the European context. Moreover, the ReCiPe 2016 (H) method is used to quantify the environmental impact per impact category based on the associated characterization factors. The ReCiPe endpoint method is used to convert the results in a single score expressed in eco-points. The method consists of three environmental protection areas: human health, ecosystem quality and resource scarcity [7]. In addition, the results are also expressed in terms of global warming potential (GWP) based on the ReCiPe midpoint method.

This contribution follows on a cradle-to-use approach considering three different phases:

- The production phase including the raw material extraction, the related transport and the manufacturing of the renovation packages,
- The construction phase including the transport from the supplier to the Smart Factory and from the Smart Factory to the site,
- The use phase including replacements and the operational energy use.

Some aspects corresponding to the construction phase and the use phase (e.g. the construction itself and maintenance) are excluded in this research due to the high uncertainties and the relatively low impact. The same applies to the end-of-life (EOL) stage since there are numerous assumptions needed [8,9]. At a later stage in the project, the EOL will be included to quantify the environmental impact of the reuse and recycling potential of the prefabricated components.

In a first stage, the environmental impact on material, energy and transport level is discussed separately. The findings of the previous paragraphs are used as a source for the LCA-input. Subsequently, the individual results are combined and compared to the non-renovated situation.

5.2. *Environmental impact of the renovation package materials*

The environmental impact of the renovation package materials is on the one hand related to the raw materials needed to produce the renovation packages based on §2 and their associated manufacturing process, and on the other hand the material impact of the required replacements during the total lifespan of the building.

Table 1. Material data of each building envelop element

façade

materials	quantity [kg/m²]	area [m²]	lifespan [years]	mass [kg]
mineral stone strips	4.80	39.7	60	190.6
adhesive mortar	3.00	39.7	60	119.1
fibreglass polyester	1.78	39.7	60	70.5
barrier spray	0.35	39.7	60	13.9
EPS	3.08	39.7	60	122.2
barrier spray	0.35	39.7	60	13.9
fibreglass polyester	1.10	39.7	60	43.7

roof

materials	quantity [kg/m²]	area [m²]	lifespan [years]	mass [kg]
roof strips	5.52	54.6	60	301.4
adhesive mortar	3.00	54.6	60	163.8
fibreglass polyester	1.78	54.6	60	96.9
barrier spray	0.35	54.6	60	19.1
EPS	3.08	54.6	60	168.1
barrier spray	0.35	54.6	60	19.1
fibreglass polyester	1.10	54.6	60	60.1

windows

materials	quantity [kg/m²]	area [m²]	lifespan [years]	mass [kg]
triple glazing	30	24.5	30	1470.0

materials	quantity [kg/m]	perimeter [m]	lifespan [years]	mass [kg]
wooden fixations	1.76	53.9	60	94.7

In this analysis only the building envelope materials are included, the integrated HVAC systems (heating, ventilation, PV) are not taken into account. Since these are major contributors due to e.g. their relative short lifespan, they will be included at a later stage.

The environmental impact of each building envelop element (i.e. façade, roof, and windows) is evaluated separately to get an idea of the proportional contribution. The material data is summarized in Table 1. Note that the fixating elements to attach the prefab panels to the existing building are not included in the calculations.

Figure 5 compares the different composing materials per building envelop element included in one renovated terraced dwelling. Whereas for the façade and the roof, the glass fibre polyester together with the insulation contribute to a significant part of the total environmental impact, the triple glazing counts most for the windows. Note that the lifespan of each material is 60 years except for the triple glazing, which has a lifespan of 30 years. During the total lifespan of the building, the glazing will thus be replaced once. This will have a considerable impact on the total environmental score given its major contribution. The relative weight of the impact of the windows transcend the impact of the other building envelope elements due to the necessary replacement.

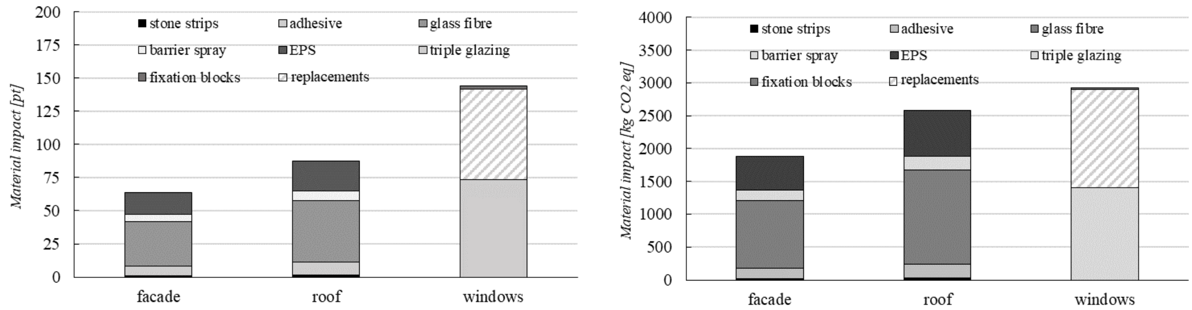

Figure 5. Material impact variation between each building envelop element in a typical dwelling

5.3. *Impact of transport*

To calculate the impact of transport a distinction is made between transport from the material extraction site to the supplier (phase 1), from the supplier to the Smart Factory (phase 2) and from the Smart Factory to the construction site (phase 3). The environmental impact of the first phase is determined based on the transport processes predefined in the Ecoinvent database. For the other two phases assumptions of the transport distances and transport means are made based on the research in §4. The applied transport data is shown in Table 2. Note that the transport model only considers one-way traffic assuming that the vehicles are used for unrelated transport on the way back.

Figure 6 compares the three transport phases. A relatively large contribution of the first phase compared to phases 2 and 3 is noticeable. Since the first phase is identical for the conventional and prefabrication renovation practice, the transport process should, in general, be optimized. Note that when comparing the scale of figure 6 with the scale of figure 5 in section 5.2 that the overall influence of transport will only represent a small part in the total environmental score. However, this factor is certainly not negligible considering the goal of INDU-ZERO where 15,000 dwelling are to be renovated each year.

Table 2. Transport data of (a) phase 2 and (b) phase 3

(a)

transport 2			
materials	**transport means**	**mass** [ton]	**distance** [km]
stone strips	Euro6 heavy truck (>16 tons)	0.492	150
adhesive mortar	Euro6 heavy truck (>16 tons)	0.283	150
fibreglass polyester	Euro6 heavy truck (>16 tons)	0.271	150
barrier spray	Euro6 heavy truck (>16 tons)	0.066	150
EPS	Euro6 heavy truck (>16 tons)	0.290	150
triple glazing	Euro6 heavy truck (>16 tons)	2.94	150
wooden fixations	Euro6 heavy truck (>16 tons)	0.095	150

(b)

transport 3			
materials	**transport means**	**mass** [ton]	**distance** [km]
façade	Euro6 heavy truck (>16 tons)	0.574	100
roof	Euro6 heavy truck (>16 tons)	0.828	100
windows	Euro6 heavy truck (>16 tons)	3.035	100

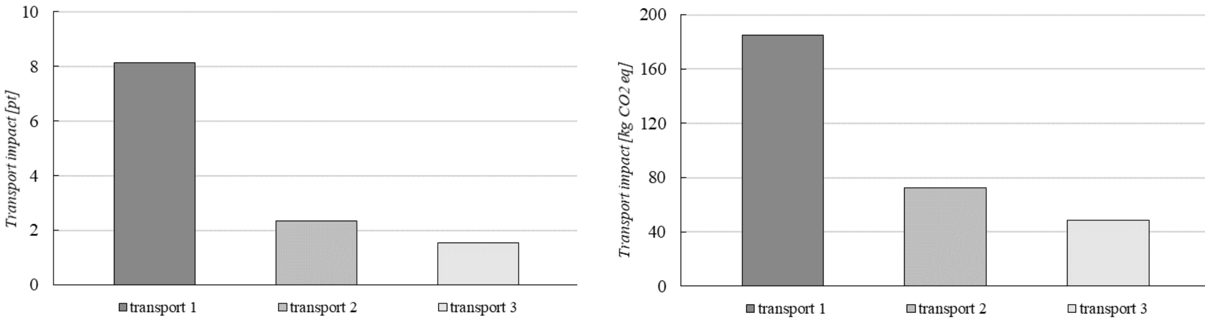

Figure 6. Transport impact variation between each transport phase

5.4. *Impact of operational energy use*

To determine the impact of the operational energy use only transmission losses and infiltration losses are considered based on the model explained in §3. This allows to only evaluate the change in performance due to the building envelope renovation, since the renewal of the technical installations is not within the scope of this paper. For this reason, an identical gas condensing boiler is assumed in the renovated and non-renovated case. An average efficiency of 0.86 is used based on a distribution, emission and control efficiency of 0.95, 0.96 and 0.94, respectively. At a later stage, the effect of including electricity as an energy source and renewables will be assessed. By renovating the building, the environmental impact during the usage phase lowers with 57% as the pre-upgrade end energy use is reduced from 216 kWh/m^2.a to 92 kWh/m^2.a considering a lifespan of 60 years.

5.5. *Total environmental impact*

As explained in the previous section, by adopting the renovation packages on the terraced dwelling, there is a 57% decrease in the environmental impact solely based on energy savings. However, this decrease is partially, yet not fully, compensated by the additional material and transport impact. The environmental impact of adding extra material is thus compensated by the obtained energy savings. This is due to the relatively high share of the operational energy use in the total environmental score. It may be possible to further increase the insulation thickness and lower the total environmental impact even more. On the other hand, the HVAC systems are currently not included in the simulations resulting in a lower environmental impact. Further research is needed to obtain a more complete picture of the total environmental impact.

Renovating the reference dwelling reduces the overall environmental impact by 54% and the GWP by 50% assuming a lifespan of 60 years. This is shown in Figure 7. Note that the reduction strongly depends on the considered lifespan. When performing a sensitivity analysis considering a lifespan of 30 years and 10 years, respectively, the reduction in the overall environmental score is only 52% and 41%. The reduction in GWP is 46% and 23%, respectively. In these cases, the relative weight of the operational energy lowers. Furthermore, the proportional contribution of each phase differs when looking at the overall score and the GWP. The material impact increases from 7% to 14%, respectively for overall impact score and the GWP. The impact of transport remains negligible. Hence, it is crucial to clearly outline the system boundaries and the impact indicators used of each LCA analysis.

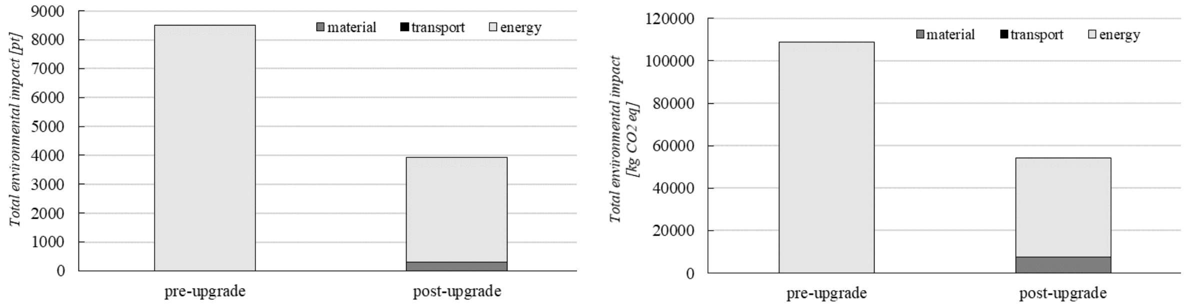

Figure 7. Total environmental impact before and after renovation

6. Conclusions

Considering the urgent need for rapid renovations to meet the 2050 targets, INDU-ZERO proposes modular prefabricated renovation packages to arrive at zero-energy dwellings in the North-Sea Region. The renovation packages consist of sandwich panels with fully integrated HVAC technologies for the wall and roof components. Due to the simplicity of the design with few different constituting parts compared to wooden and metal frame panels, the environmental material impact is relatively low. The application of these renovation packages to an archetypical building reduces the final energy use with 41% based on results obtained with a quasi-steady state heat balance model. Additionally, the renovation package design prioritizes repeatability of production processes and mass production to produce large amounts of fully integrated renovation package components in short time. Within this philosophy, big logistic challenges are to be tackled. Optimizing the supply chain and transport management can lead to annual savings of more than 4 Mton CO_2 balancing the effect of the additional transport from supplier to the Smart Factory compared to the conventional means of transport. Finally, not only the environmental impact of transport is important, but also how many resources and energy are spent in the production and usage phase. Considering the total ecological impact, the production and transport phase related to the renovation packages are compensated by the operational energy savings compared to the non-renovated situation showing a reduced impact of 54% assuming a lifespan of 60 years.

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