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# Energy and carbon balance of materials used in a building envelope renovation

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**Abstract.** Construction and demolition waste (CDW) are a priority waste stream in EU's polices, accounting for about 30% of all waste generated. At the same time, according to the EU energy-efficiency directive, existing buildings subject to significant renovation need to be upgraded in their thermal building envelope in order to meet higher energy performance standard. This involves additional building materials and hence increases the CDW generation. This study investigates the energy and $CO_2$ emission balance of building envelope renovation when using different building materials, taking into account the production and end-of-life stages. The study is based on a Swedish case-study building assumed to be upgraded to the passive house standard. Benefits from waste recovering are considered, including construction and demolition wastes. The results show that the selection of building materials can significantly affect the primary energy and $CO_2$ emission balances. Depending on the material alternative the end-of-life primary energy use and net $CO_2$ emission can be reduced by 5%-21% and 2%-24%, respectively, compared to the initial primary energy use and net $CO_2$ emission. Therefore, a careful material choice at the design stage, as well as an efficient waste management, can contribute to reduce primary energy use and $CO_2$ emission associated with energy renovation of existing buildings.

**Keywords:** building renovation, construction and demolition waste, end-of-life, primary energy, $CO_2$ emission.

## 1. Introduction

The building sector is responsible for a large consumption of energy and material resources, as well as for a rising waste generation worldwide. The sector accounts for over 40% of the global primary energy use [1] and for about 50% of the global raw material extractions [2]. Furthermore, construction and demolition waste (CDW) contributes to over 25% of all waste generated [2].

In Europe, the existing building stock is mainly composed of residential buildings, accounting averagely for 75% of the total floor area, and more than 80% of them was built before 1990 [3]. This is because the rate of the building stock replacement is low: the annual demolition rate was between 0.025% and 0.23%, while the annual construction rate was about 1% [4]. Therefore, building renovation is important to upgrade the residential sector over time. In addition, renovation for energy-efficiency purpose is prioritised by the EU energy policy in order to fulfil high energy-efficiency standard from 2020 [5]. The passive house standard is consistent with the EU energy-efficiency standard.

Buildings' life cycle encompasses production, construction, operation and end-of-life stages that all contribute to energy use and climate impacts. Although the operation phase still accounts for the highest share of primary energy use in conventional buildings [6], studies are clear in showing the importance of primary energy use and $CO_2$ emission in the production phase [7,8,9] but few studies include the end-of-life phase. Thormark [10] compared two different end-of-life scenarios of a passive house, showing negligible energy use for waste transport but significant energy saving from recycling activities, equal to 35% of the production energy maximising material recycling. Thormark [11] compared two versions of a passive house using alternative materials, finding that the recycling potential is comparable. Fouquet et al. [12] compared timber- and concrete-framed low-energy houses, finding that the end-of-life $CO_2$ emissions are comparable, but the net $CO_2$ emission of the timber-framed house can vary significantly depending on the disposal scenario.

CDW could be assumed to replace primary materials without any impacts, obtaining gross benefits according to the zero-burden assumption. Alternatively, the recycling potential assumption could be used, where impacts from recycling activities are considered to obtain net benefits. Blengini [13] analysed the demolition of a multi-storey building and considered steel and concrete waste, showing that the energy saving calculated as gross benefit is 83% and 20% higher than that calculated as recycling potential. The corresponding numbers for avoided $CO_2$ emission were 66% and 22%.

In this study, we investigate the production and end-of-life primary energy and carbon balances of thermally-equivalent building envelopes with different materials, using the recycling potential approach.

## 2. Method

### *2.1. General approach*
Our methodological approach consists of the following steps: (i) improving the thermal performance of the case-study building with retrofit measures to meet the passive house standard; (ii) varying building materials in the retrofitted building envelope to achieve different material versions with equal energy-efficiency standard; (iii) analysing the primary energy use and $CO_2$ emission of the material versions in the production and end-of-life stages; (iv) comparing the primary energy and carbon balances of the material versions.

### *2.2. Case study*
An existing 3-storey residential building is used to model and design the retrofitted building envelopes analysed in this study. The building has 2000 $m^2$ of heated floor area and 27 apartment units with a basement of 600 $m^2$ below the ground level. The building, constructed in 1972, is sited in Southern Sweden and is a typical Swedish concrete-framed multi-family house from the 1970s [14]. The existing envelope has a rather poor thermal insulation and is covered with brick and wood walls, alternatively.

*2.2.1. Retrofitted building envelopes.* Based on the architectural design of the existing building, we modelled different thermally-improved building envelopes designed to meet the passive house standard. The annual energy consumption for space and tap water heating was taken to be 30 $kWh/m^2$, corresponding to the Passive House Institute (PHI) standard for retrofitted buildings. The whole retrofitted building was modelled with the VIP-Energy software [15], which performs dynamic hourly-based energy modelling and is validated by the IEA's building energy simulation test and diagnostic methods. The U-value of the existing building envelope was improved to about 0.14 $W/m^2K$ in the external and basement walls, 0.9 $W/m^2K$ in the attic floor and 0.6 $W/m^2K$ in the windows. The airtightness of the existing building is taken to be 0.8 l/s $m^2$ at 50 Pa, based on [16], and this is assumed to be improved to 0.6 l/s $m^2$ in the retrofitted building. Further details about input data of the building modelling are in [17]. Based on the energy modelling of the retrofitted building, we compare thermally-equivalent building envelopes using alternative building materials for three building elements: (i) thermal insulation; (ii) building cladding; (iii) window frame. The selection of building materials is based on the Swedish building sector. The insulation materials are: glass wool (G); rock wool (R) and wood fibre (W). Extruded polystyrene is used in the basement walls. The cladding materials are: brick (B); aluminium (A) and wood (W). The window-frame materials are: aluminium (A) and wood (W). Finally, alternative building materials are combined together to compare eighteen material versions, as shown in Table 1.

*2.3. Scenario*

We assume the retrofitted building envelopes to have a life span of 50 years. We also assume that each retrofitted building envelope is assembled at the current time and disassembled after 50 years. A dominant recycling of CDW is considered. To calculate the primary energy and carbon balance the following key factors were considered: materials' end-of-life option, CDW recovery rate and CDW recycling efficiency. For the effective recovery rate and recycling efficiency of CDW, we used a current scenario for the assembly phase and a future scenario for the disassembly phase.

*2.3.1. Aluminium*. In Sweden, aluminium scrap can be processed in secondary aluminium production plants to produce cast aluminium alloys [18]. In the current scenario, the aluminium recovery rate is taken to be 90% [19]. However, in the future scenario, the recovery rate is supposed to be 98% [20]. Old aluminium scraps are efficiently recovered to produce secondary aluminium instead of primary aluminium from alumina. The recycling efficiency is taken to be 96% [21] in both scenarios.

*2.3.2. Brick*. In North European countries, the recovery rate of demolished bricks is low [22]. Recovered bricks are commonly crushed and used for backfilling [23]. In the current scenario, the recovery rate of the brick tiles is assumed to be 90%, based on [24]. In the future scenario, the recovery rate is expected to increase to 95% due to EU policies [25]. The recycling efficiency is taken to be 60% in both scenarios, while the 40% of the crushed bricks are transferred to the fine fraction and then landfilled [26].

*2.3.3. Glass*. In Sweden, recovered flat glass is mainly transported to Germany due to the lack of specialised recycling facilities [18]. However, the flat glass waste is commonly sent to landfill [23]. In the current scenario, the recovery rate is equal to 0%. In the future scenario, the recovery rate is expected to increase due to EU policies [25] and recent advancements in sorting techniques [27,28]. The future recovery rate and recycling efficiency are taken to be 50% and 120%, respectively [27].

*2.3.4. Mineral wool*. Mineral wool waste, including glass and rock wool, is commonly sent to landfill. In the current scenario, the recovery rate of the mineral wool is zero. However, improvements in recycling method may increase the rate of recycled mineral fibres into new mineral wool [29]. In the future scenario, the recovery rate is taken to be 90% [30,31]. Some research projects [32,33], aimed at increasing the recycled content in new mineral wool, find that about 80% of the recovered process waste can substitute over 7% of the total amount of raw materials [33]. We assume equivalent recycling efficiency for mineral wool waste.

*2.3.5. Wood*. Since 2005, landfilling of organic waste has been prohibited in Sweden [34]. We assume that the demolished wood is clean and recovered for bioenergy, since this is a common practice [23]. The recovery rate is taken to be 90% [35] and is supposed to increase to 95% in the future scenario. The remaining waste is assumed to decay into $CO_2$ released to the atmosphere. Wood waste is assumed to replace fossil coal, with a relative conversion efficiency of 0,98.

*2.3.6. Extruded polystyrene (XPS).* In Northern European countries, insulation foams can be incinerated [36]. We assume that XPS insulation is incinerated to produce electricity. In the current scenario, the recovery rate is taken to be 90% [36]. In the future scenario, the recovery rate is supposed to increase to 95% due to EU policies [25]. XPS waste is assumed to replace fossil coal. The conversion efficiency of a municipal incineration plant is taken to be two thirds of a fossil coal plant [37]. XPS waste has a lower heating value equal to 11.4 kWh/kg [38].

### 2.4. Material inventory

The mass of materials required to retrofit the building envelope under different material version (Table 1) is calculated from the design of the new building envelopes based on the building energy modelling. The inventory does not include materials for heating system. The wood waste from 1 kg of manufactured wood is calculated based on Ecoinvent flow data [39], resulting in: 55% for sawn timber and 38% from sawing and 7% from planning. The calculation of the waste mass on the construction site is calculated as a percentage of the material mass based on [40], as follow: 7% insulation waste, 10% plasterboard and wood waste, 5% for all other materials.

**Table 1.** Material quantities (tons) in the material versions of the retrofitted building envelope (acronyms are composed by the initial letters of the materials used in thermal insulation, cladding and window frame, respectively – e.g. GBA, where G=glass wool in thermal insulation, B=brick in cladding, A=aluminium in window frame).

| | GBA | GBW | GAA | GAW | GWA | GWW | RBA | RBW | RAA | RAW | RWA | RWW | WBA | WBW | WAA | WAW | WWA | WWW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Thermal insulation* | | | | | | | | | | | | | | | | | | |
| Glass wool | 4 | 4 | 4 | 4 | 4 | 4 | | | | | | | | | | | | |
| Rock wool | | | | | | | 7 | 7 | 7 | 7 | 7 | 7 | | | | | | |
| Wood fibre | | | | | | | | | | | | | 7 | 7 | 7 | 7 | 7 | 7 |
| *Cladding* | | | | | | | | | | | | | | | | | | |
| Brick | 65 | 65 | | | | | 65 | 65 | | | | | 65 | 65 | | | | |
| Aluminium | | | 3 | 3 | | | | | 3 | 3 | | | | | 3 | 3 | | |
| Wood | | | | | 15 | 15 | | | | | 15 | 15 | | | | | 15 | 15 |
| *Window frame* | | | | | | | | | | | | | | | | | | |
| Aluminium | 1 | | 1 | | 1 | | 1 | | 1 | | 1 | | 1 | | 1 | | 1 | |
| Wood | | 2 | | 2 | | 2 | | 2 | | 2 | | 2 | | 2 | | 2 | | 2 |
| **Total** | **70** | **71** | **8** | **9** | **20** | **21** | **73** | **74** | **11** | **12** | **23** | **24** | **73** | **74** | **11** | **12** | **23** | **24** |

### 2.5. System boundary

The study includes the production and end-of-life stages. The operation stage is assumed to give equal primary energy use and $CO_2$ emission for all the retrofitting options. The construction stage is neglected.

#### 2.5.1. Production stage

*Primary energy*. The net production energy is the primary energy used to manufacture the materials, minus the net energy from the biomass recovery for energy purpose. The manufacture primary energy use is calculated based on Ecoinvent data [41] adjusted in order to account coal as sole source of marginal electricity. The net energy from biomass recovery is calculated as the heating value of the overall biomass residues, minus the energy used to transport and process the residues. The lower heating values of the processing residues are calculated from [42] but adjusted according to the Swedish context, resulting in: 3.09 kWh/kg for thinning residues, 4.17 kWh/kg for sawing residues and 5.39 kWh/kg for planing residues [34]. The fuel-cycle energy use is 5% for thinning and 1% for other activities [34].

*$CO_2$ emission*. The net $CO_2$ emission is calculated as the $CO_2$ emission due to the manufacture of materials, minus the $CO_2$ emission avoided by replacing fossil fuel with recovered wood waste. The manufacture $CO_2$ emission is calculated based on Ecoinvent data adjusted in order to account for $CO_2$

emission from the coal-sourced electricity and that carbon stock in wood materials are excluded. The total coal-sourced $CO_2$ emission are calculated by multiplying the primary energy use by the specific fuel-cycle carbon intensity of coal, that is taken to be 0.385 kg $CO_2$/kWh [43]. The net $CO_2$ emission from biomass recovery is calculated as the avoided $CO_2$ emission by substituting fossil coal, minus the $CO_2$ emission of the fossil fuel used to recover and transport the biomass. Diesel fuel is assumed as transport fuel. The fuel-cycle carbon intensity of motor diesel is taken to be 0.29 kg $CO_2$/kWh [44].

*2.5.2. End-of-life stage*

*Primary energy*. The net end-of-life primary energy is calculated as the primary energy used to sort and transport CDW, minus the energy saving from the recycling of CDW until the end-of-waste state. Ecoinvent data do not consider primary energy use for demolition of the investigated materials [26]. The sorting and transport primary energy is calculated based on Ecoinvent data [41] adjusted in order to account for Sweden-sited haul distances, as follow: 10 km for landfill and processing site, 90 km for incineration plant and, for the recycling plants, 100 km for aluminium, 200 km for mineral wool and gypsum, 1000 km for glass. Basing on [45], transportation occurs by a diesel-fuelled middle-sized truck of 26 tons with a capacity of 70%. Fuel consumption of trucks is taken to be 32 l/100 km [46] in the current and future scenario. The energy savings from CDW recycling is equal to the production primary energy of the substituted primary materials multiplied by the recovery rate and recycling efficiency of the CDW. The energy savings from CDW combustion is calculated as the heating value of CDW multiplied by relative conversion efficiency between the municipal incineration plant and the coal-based plant and the fuel-cycle energy of coal. The energy use from landfilling is neglected.

*$CO_2$ emission.* The net $CO_2$ emission is calculated as the $CO_2$ emission for sorting and transport of CDW, minus the avoided $CO_2$ emission from the recycling of CDW until the end-of-waste state. The sorting and transport $CO_2$ emission is calculated based on Ecoinvent data [41] adjusted in order to account actual $CO_2$ emissions from Sweden-sited haul distances. The avoided $CO_2$ emission from CDW recycling is equal to the production $CO_2$ emission of the substituted primary materials (see Paragraph 2.5.1.2) multiplied by the recovery rate and recycling efficiency of the substituting CDW. $CO_2$ emission from recovery of burnable fossil-based CDW (i.e. XPS) is equal to the $CO_2$ emission from CDW, minus the avoided $CO_2$ emission by substituting fossil fuels, multiplied by the relative conversion efficiency between the municipal incineration plant and the coal-based plant and the fuel-cycle carbon intensity of coal.

## 3. Results

Tables 2 and 3 show the primary energy and $CO_2$ emission, respectively, to produce and to dispose the eighteen material versions of the retrofitted building envelope. The primary energy balance ranges between 1599 MWh and 2693 MWh, where the low-energy version has wood fibre insulation, wood cladding and wood-framed windows (WWW) and the high-energy version has glass wool insulation, brick cladding and aluminium-framed windows (GBA). The carbon balance ranges between 399 $tCO_2$ (WWW) and 594 $tCO_2$ (GAA), for the low- and high- material versions, respectively.

In the production phase, the low-energy version is WWW, with primary energy use of 2195 MWh. The high-energy version has glass wool insulation, aluminium cladding and aluminium-framed windows (GAA) and primary energy use of 2862 MWh. The bioenergy recovery can reduce the net production primary energy use by up to 8% in wood material versions. The net $CO_2$ emission ranges between 471 $tCO_2$ and 662 $tCO_2$, where the low- and high-carbon versions are different from the low- and high-energy versions in the production stage. The bioenergy recovery can also reduce the manufacture $CO_2$ emission by up to 12% in wood material versions. The lowest values of bioenergy recovery are achieved with the wood cladding, due to the high rate of recoverable biomass residues.

In the end-of-life phase, the low-energy version has wood fibre insulation, wood cladding and wood-framed windows (WWW) and the high-energy version has glass wool insulation, brick cladding and aluminium-framed windows (GBA), giving primary energy use of -416 MWh and -134 MWh, respectively. The transport energy does not affect the final results, ranging between 1 MWh and 2 MWh. The disposal energy, that is the sum of energy use for sorting and energy saving from CDW recycling, is negative due to the dominant recycling of recovered materials. The lowest values of disposal energy are achieved with wood cladding, followed by aluminium cladding, due to the high specific energy recoverable from aluminium recycling. The net $CO_2$ emission ranges between -126 $tCO_2$ and -13 $tCO_2$. The high-carbon versions are GBA, which is the same as the high-energy version, and GAA. This is due to the little contribution of brick and aluminium recycling to avoided $CO_2$ emission. The lowest values of disposal $CO_2$ emission are achieved with the wood cladding. Depending on the material version, the production primary energy use and $CO_2$ emission can be reduced by 5%-21% and 2%-24%, respectively.

**Table 2.** Primary energy (MWh) of the material versions of the building envelope.

| | GWA | GWW | GBA | GBW | GAA | GAW | RWA | RWW | RBA | RBW | RAA | RAW | WWA | WWW | WBA | WBW | WAA | WAW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Production stage* | | | | | | | | | | | | | | | | | | |
| Manufacturing | 2702 | 2650 | 2827 | 2775 | 2862 | 2809 | 2483 | 2431 | 2613 | 2561 | 2649 | 2597 | 2247 | 2195 | 2377 | 2325 | 2413 | 2361 |
| Bioenergy recovery | -161 | -184 | 0 | -23 | 0 | -23 | -157 | -180 | 0 | -23 | 0 | -23 | -157 | -180 | 0 | -23 | 0 | -23 |
| Total from production | 2541 | 2466 | 2827 | 2752 | 2862 | 2786 | 2326 | 2251 | 2613 | 2538 | 2649 | 2574 | 2090 | 2015 | 2377 | 2302 | 2413 | 2338 |
| *End-of-life stage* | | | | | | | | | | | | | | | | | | |
| Transport | 2 | 2 | 1 | 1 | 1 | 1 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 |
| Disposal | -365 | -370 | -135 | -141 | -202 | -208 | -358 | -364 | -136 | -142 | -206 | -211 | -413 | -418 | -211 | -217 | -278 | -284 |
| Total from end-of-life | -363 | -368 | -134 | -140 | -201 | -207 | -356 | -362 | -135 | -141 | -205 | -210 | -412 | -416 | -210 | -216 | -277 | -283 |
| **Total** | **2178** | **2098** | **2693** | **2612** | **2661** | **2579** | **1970** | **1889** | **2478** | **2397** | **2444** | **2364** | **1678** | **1599** | **2167** | **2086** | **2136** | **2055** |

**Table 3.** $CO_2$ emission ($tCO_2$) of the material versions of the building envelope.

| | GWA | GWW | GBA | GBW | GAA | GAW | RWA | RWW | RBA | RBW | RAA | RAW | WWA | WWW | WBA | WBW | WAA | WAW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Production stage* | | | | | | | | | | | | | | | | | | |
| Manufacturing | 725 | 724 | 606 | 604 | 615 | 614 | 651 | 649 | 536 | 534 | 545 | 544 | 596 | 595 | 481 | 480 | 491 | 489 |
| Bioenergy recovery | -63 | -71 | 0 | -9 | 0 | -9 | -61 | -70 | 0 | -9 | 0 | -9 | -61 | -70 | 0 | -9 | 0 | -9 |
| Total from production | 662 | 653 | 606 | 595 | 615 | 605 | 590 | 579 | 536 | 525 | 545 | 535 | 535 | 525 | 481 | 471 | 491 | 480 |
| *End-of-life stage* | | | | | | | | | | | | | | | | | | |
| Transport | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Disposal | -102 | -107 | -13 | -18 | -21 | -27 | -100 | -105 | -13 | -19 | -21 | -27 | -121 | -126 | -43 | -49 | -51 | -57 |
| Total from end-of-life | -102 | -107 | -13 | -18 | -21 | -27 | -100 | -105 | -13 | -19 | -21 | -27 | -121 | -126 | -43 | -49 | -51 | -57 |
| **Total** | **560** | **546** | **593** | **577** | **594** | **578** | **490** | **474** | **523** | **506** | **524** | **508** | **414** | **399** | **438** | **422** | **440** | **423** |

## 4. Uncertainties

The material mass is increased based on [40] to include wastage on the construction site. However, the use of ready-to-install building claddings (i.e. aluminium sheets and brick tiles) might reduce it.

The specific production energy and $CO_2$ emission of materials are based on Ecoinvent process data, which reflect the Swiss and European production patterns and thereby are not site-specific for Sweden.

The recovery rate and recycling efficiency of CDWs depend on a number of factors changing over time, such as the European and national waste policies, waste management practices and industrial technologies. In the current scenario, comprehensive data is lacking on recovery and recycling of CDWs and such data need to be improved. In the future scenario, the recovery rate and recycling efficiency of CDWs are uncertain because of difficulties in forecasting technology development. Furthermore, the Ecoinvent data does not consider current best available technology or technology development as the data is inventoried based on then used average technology [47]. Hence, we might underestimate the efficiency of future industrial technologies when adopting Ecoinvent data.

This study assumes CDWs to be recycled, recovered for energy purpose or landfilled, alternatively. However, CDWs can also be reused as materials and wood process waste can be recycled. This may become increasingly important in the future, to gain additional value from also reusing materials [34].

## 5. Discussion and conclusion

The results of this study show that the choice of insulation, cladding and window materials when retrofitting a building's envelope has a significant impact on primary energy and carbon balance.

At the production phase, wood materials may play an important role in reducing primary energy use and $CO_2$ emission, especially when the woody residues from manufacture processes are recovered and used for bioenergy instead of fossil energy. At the end-of-life phase, the energy recovery of wood waste can significantly contribute to reduce both end-of-life primary energy and $CO_2$ emission. Aluminium recycling could give end-of-life primary energy benefit but with a relative increase of $CO_2$ emission. Other recycling processes have marginal benefits. For example, crushed brick aggregate entails higher primary energy use in comparison to the extraction of natural aggregate, resulting in net primary energy increase. A life cycle perspective and good practice could help to select suitable building materials for different building parts, compatible with architectural and technical requirements. The use of prefabricated building elements may reduce wastage on-site while a careful design of the building elements may facilitate the disassembly and minimize damages, and thereby improve the recovery rate of CDW.

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