

Article

Carbon Footprints of a Conventional Norwegian Detached House Exposed to Flooding

Line Berg Oppedal * and Tore Kvande 

Department of Civil and Environmental Engineering, Norwegian University of Science and Technology (NTNU), 7034 Trondheim, Norway; tore.kvande@ntnu.no

* Correspondence: linebop@stud.ntnu.no

Abstract: Rehabilitating water-damaged structures in buildings results in increased material extraction and energy use, and, consequently, a higher carbon footprint of the housing industry. Despite its prevalence, quantifying the carbon footprint caused by water damage or flooding has not gained much attention. Thus, this study investigated the quantitative carbon footprint associated with rehabilitating flooding in a detached house caused by torrential rain. Three different construction methods of the house were looked at; a timber frame construction, a masonry variant made by concrete blocks of Lightweight Expanded Clay Aggregate (LECA), and an alternative with exterior walls composed of concrete-moulded Expanded Polystyrene (EPS) foam boards. A life-cycle assessment according to NS 3720 was used to investigate the carbon footprint ($\text{CO}_{2\text{eq}}$) of typical flooding in a detached building. Rehabilitating the flooding in a house with concrete-moulded boards resulted in a lower carbon footprint ($2.45 \times 10^3 \text{ CO}_{2\text{eq}}$) than rehabilitating the same flooding in a house with LECA masonry ($7.56 \times 10^3 \text{ CO}_{2\text{eq}}$) and timber frames ($2.49 \times 10^3 \text{ CO}_{2\text{eq}}$). However, the timber-frame house had the lowest total carbon footprint ($2.95 \times 10^4 \text{ CO}_{2\text{eq}}$) owing to their original low footprint. This study found that flooding significantly contributed to the carbon footprint of buildings and, therefore, the topic should be given attention when choosing a construction method and moisture safety strategy.

Keywords: construction methods; life-cycle assessment; global warming potential; carbon footprint; moisture; torrential rain



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1. Introduction

Since 1850, the global average temperature has increased by 1.1 °C, which is the fastest temperature increase scientists have observed in Earth's history, owing to increased emissions of greenhouse gases [1]. This temperature change has resulted in warmer oceans, melted polar ice caps, and more variable and extreme weather conditions worldwide. To stop this temperature increase, it is necessary to reduce global greenhouse gas emissions. A report by United Nations Environment Programme [2] showed that buildings (residential and non-residential) accounted for 37% of the global CO_2 emissions in 2021 when including estimated CO_2 emissions from producing buildings materials of around 3.6 GtCO_2 (i.e., concrete, steel, aluminium, glass, and bricks) accounting for 9% of the total.

Because the building industry has a significant carbon footprint, it is important to minimise unnecessary emissions such as building defects. In this study, a building defect was considered according to the definition provided by Ingvaldsen [3]: 'A damage or flaw that compromises the quality of the building or building part'. The types of information sources available regarding building defects were mapped in [4]. Building defects are often attributable to poor design, workmanship, and management [5–7]. Rehabilitating building defects is a significant part of the turnover in the construction industry [8–10]. The avoidance of building defects can decrease the carbon footprint and economic losses of buildings. Few studies have been conducted on the carbon footprint of building defects.

Andenæs et al. [11] investigated the carbon footprint of roof leakages; however, similar research remains lacking.

Studies from Sweden [12] and Norway [13] have found that 81% and 76% of all building-related damage, respectively, is owed to moisture exposure. The primary sources of moisture damage are leakage, precipitation, groundwater, internal moisture, and built-in moisture [13]. Between 2014 and 2023, 218,348 cases of weather-related water damage owing to external water intrusion including flooding were reported by the finance industry in Norway [14]. Intrusion occurs through the foundation, roof, exterior walls, gutters, surface water drainage pipes, and drainage pipes. These damages amounted to EUR 883 million [14].

A report by The Norwegian Climate Service Centre for the Norwegian Environment Agency found that the incidence of torrential rain is becoming more intense and is expected to occur more frequently [15]. In the United Kingdom, a similar development of extreme rainfall events has been reported [16]. Consequently, increasing amounts of flooding must be rehabilitated annually. In Norway, considerable flooding was reported in August 2023 owing to the extreme weather event ‘Hans’ [17]. Torrential rain caused landslides and floods, which resulted in 13,800 damage cases and costing EUR 186 million [17]. Other countries have the same challenge with torrential rain as well. E.g., there were two extremely heavy rainfall episodes in 2007 in Britain, which resulted in insurance claims of EUR 3.5 billion [18]. According to [19], the number of Canadian insurance claims owing to heavy rainfall episodes is expected to increase by 13% in 2016–2035, 20% in 2046–2065, and 30% in 2081–2100. However, the carbon footprint of rehabilitating these damages have not yet been investigated.

To rehabilitate water-damaged buildings caused by torrential rain, wet materials must be adequately dried before they can be covered with new materials [20,21]. There are three primary drying methods: (1) natural drying, (2) heating and ventilation, and (3) dehumidification and ventilation. Drying via dehumidification and ventilation is usually recommended because it provides the fastest and most controlled drying for mould growth [21]. Different materials have varying drying times depending on the temperature, relative humidity (RH), material type, moisture content, covering, thickness of the material and construction, and critical moisture conditions [22,23]. Regardless of the drying method and drying time, drying requires energy and thus contributes to greenhouse gas emissions.

Rehabilitating water-damaged buildings caused by torrential rain may also require the replacement of damaged building materials like, e.g., wood-based floorings, gypsum boards, and interior doors. Normally, the carbon footprint of a building material refers to the total amount of greenhouse gases released during its lifecycle, characterised in kg CO₂ equivalents [24]. Manufacturers document the carbon footprint of their items in the Environmental Product Declaration (EPD) in accordance with standard NS-EN 15804:2012 [25]. The EPD shows the environmental impact of a product at each stage of its life, including production and installation (A), use (B), end-of-life (C), and beyond-lifetime (D). In this study, replacing materials were investigated; therefore, phases A, C, and D were considered. The use phase is, hence, omitted also because we do not know when a potential flooding appears during the lifespan.

Wood is considered a sustainable material because of its biogenic carbon storage [26,27]; however, it is also a moisture-sensitive material that can be damaged when exposed to moisture [28]. With the significant increase in precipitation expected in the future [15], we anticipate an increase in flooding [17]. Hence, this study aimed to determine whether timber-frame houses are a more sustainable construction method in terms of carbon footprint than masonry and concrete houses when exposed to flooding caused by torrential rain. This study investigated the rehabilitation of flooding in three different construction methods based on the following research questions:

1. What is the carbon footprint of a typical new Norwegian single-family residential building constructed using different methods?;

2. What is the carbon footprint of rehabilitating flooding caused by torrential rain using different construction methods?;
3. What is the potential carbon footprint of flooding caused by torrential rain in Norway?

This study was limited to investigating imaginary water damage situations owing to the lack of available data on actual comparable flooding. In addition, the global warming potential (GWP) was calculated for only one house model. The intention of this study is to put the attention on the topic and not to provide a thorough estimate for the entire situation in Norway. A total estimate for Norway needs a model for the building damage situation that is not within the scope of this study.

2. Case, Materials, and Methods

2.1. Case

The house model «Arv» used in this study represents a typical modern Norwegian detached house, as shown in Figure 1. The original house model was designed as a timber-frame house, and the entire set of building plans and list of construction materials were made available for the authors by Norgeshus. «Arv» comprises a concrete slab on the ground, a hip roof structured by a wooden roof truss, and a floor of wood-based I-profile beams. Ceramic tiles exist at entrances, bathrooms, and laminate flooring elsewhere. The house had a footprint of 93.6 m² and a heated floor area of 171 m². Figure 2 shows the ground floor of the house.



Figure 1. Case building, «Arv». Concept illustration: Norgeshus.

The timber-frame house was redesigned in accordance with the Norwegian Regulations on technical requirements for construction works [29] and the SINTEF Building Research Design Guides [30] as a LECA masonry house, which is composed of concrete blocks of Lightweight Expanded Clay Aggregate, and as a house with exterior walls composed of concrete-moulded Expanded Polystyrene (EPS) foam boards. A typical flooding was selected based on information from a specialist on water and flooding damage from the leading property damage restoration firm in Norway, Polygon AS, and from a joint workshop with experts from SINTEF, a building research organisation, see Section 2.3.

The total environmental impact of the construction materials used was calculated according to NS 3720:2018 [31] using the declared data from the Environmental Product Declarations (EPDs). The carbon footprints of the three houses and reconstruction owing to flooding were calculated via the addition of the GWP of materials (equivalent-CO₂ emissions, expressed as kg CO_{2eq.}). All calculations (excel spreadsheets) are available as Supplementary Materials. The EPDs for different construction materials were mostly

obtained from the Norwegian EPD foundation database. The EPDs for the remaining products were found at EPD online. The declared GWP for stage A1–5, C1–4, and D from the EPDs were included. Because the user stage B data are often absent from EPDs and since maintenance, repair, refurbishment, etc., were not relevant in this study, stage B was eliminated. The assumed transport distance from the EPDs (A4) was used because the house model is a concept rather than a constructed house.

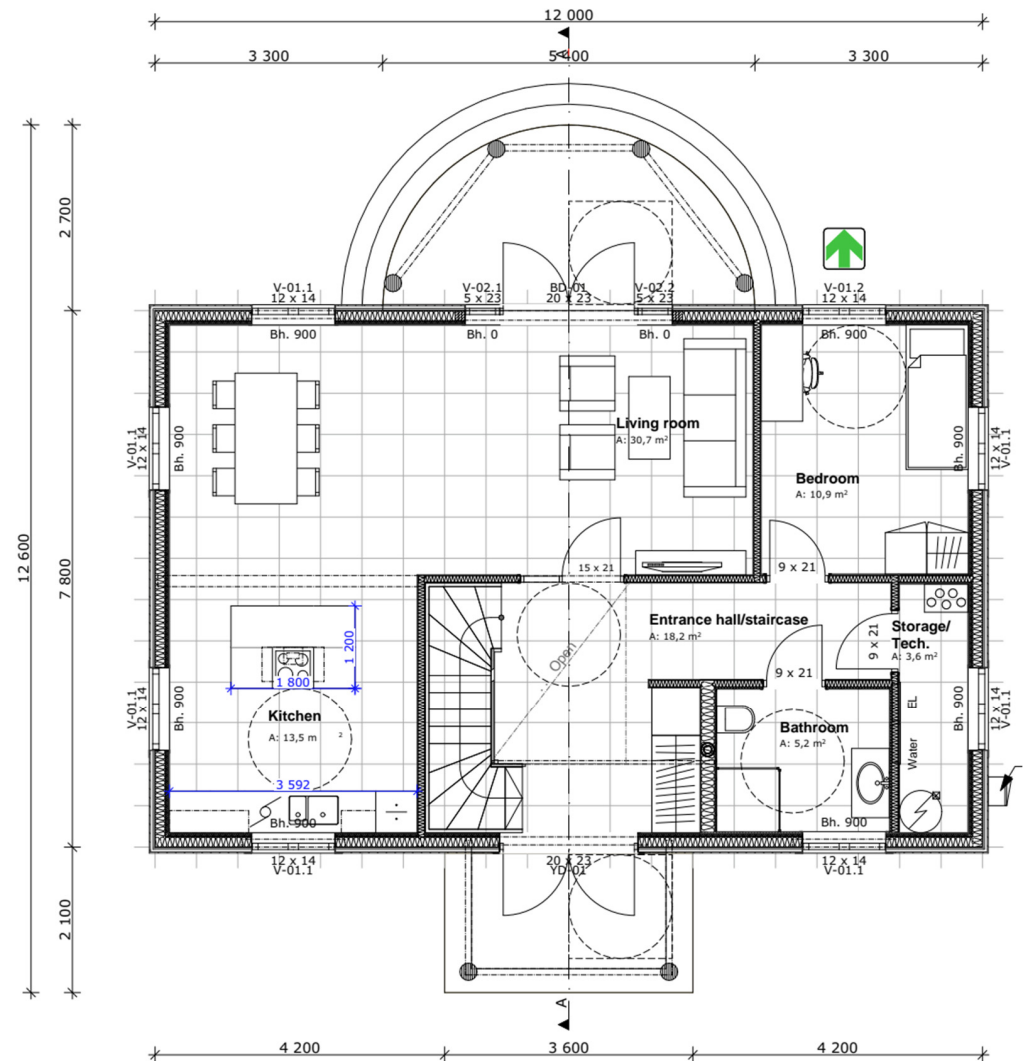


Figure 2. Ground floor of the original timber frame version. All dimensions are in mm. Concept illustration: Norgeshus.

Technical installations like plumbing, ventilation, and electricity were not included in the GWP calculations because this study only considered emissions associated with construction materials and their replacement. In addition, built-in furniture was not considered, because it was not included by Norgeshus in their shared material calculations.

2.2. Construction Methods and Materials

The three houses had different wall constructions but had the same floor construction between the ground floor and the first floor and the same roof construction. The following sections describe the three wall constructions, including the quantities and EPDs of materials.

2.2.1. Timber-Frame Walls

The original timber house had exterior walls of 150 mm insulated frame walls with a 50 mm insulated lining. The interior cladding was composed of gypsum boards, and the exterior cladding was wooden. The exterior walls are shown in Figure 3. The interior walls were insulated frames with 100 mm isolation. Table 1 lists the construction materials and quantities of the timber-frame walls.

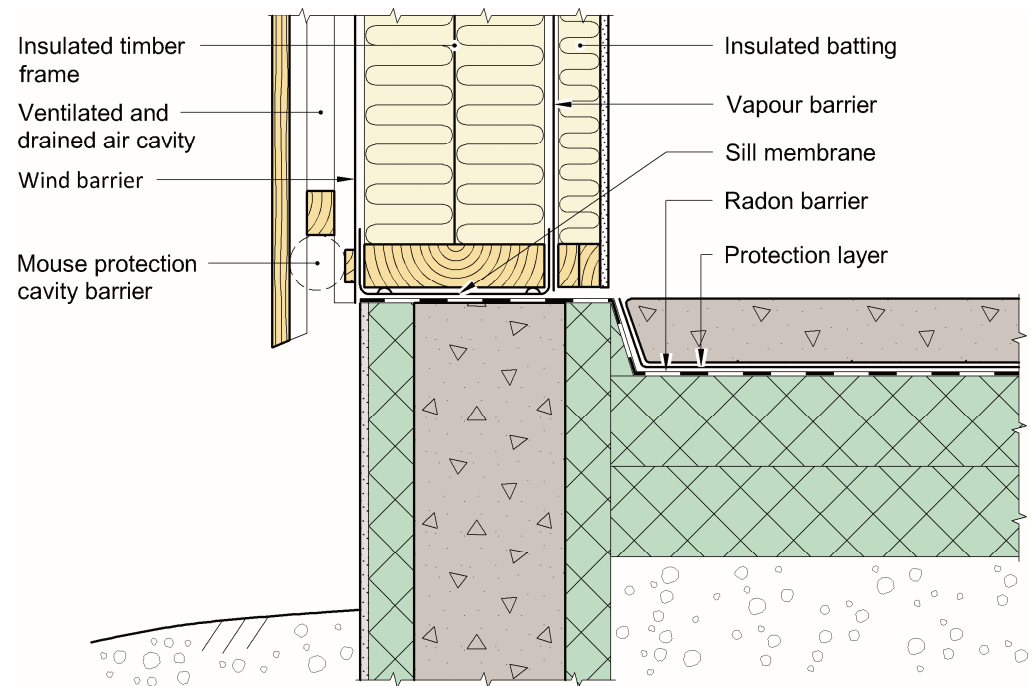


Figure 3. Foundation of timber frame exterior wall. Illustration: SINTEF Community.

Table 1. Construction materials for the exterior and interior timber-frame walls.

Building Element	Product	Quantity	Declared Unit (DU)	kg CO _{2eq} /Unit (A1–A5)	kg CO _{2eq} /Unit (C1–C4)	kg CO _{2eq} /Unit (D)	Ref. (EPD)
Exterior wall							
Foundation	Jackson	42.58	m	7.10	1.11×10^{-1}	-8.13×10^{-6}	[32]
Battens. exterior walls	Pine or spruce	3.09	m ³	-7.01×10^2	8.09×10^2	-3.40×10^1	[33]
Structural timber. walls	Spruce C24	6.09	m ³	-5.92×10^2	6.79×10^2	-1.65×10^2	[34]
Exterior cladding	Spruce	4.56	m ²	-7.01×10^2	8.09×10^2	-3.40×10^1	[33]
Vapour barrier	Baca vapour barrier	547.56	m ²	5.44×10^{-1}	0	0	[35]
Insulation	Glava glasswool	131.09	m ²	2.47×10^{-1}	2.29×10^{-3}	-8.40×10^{-3}	[36]
Interior cladding	Gyproc	198.00	m ²	2.18	1.43×10^{-1}	0	[37]
Painting	Lady pure colour	59.62	kg	3.13	1.32×10^{-2}	0	[38]
Skirt boards floor/wall	Moelv pine	0.21	m ³	-5.64×10^2	8.34×10^2	-4.26×10^1	[39]
Ceiling skirting	Moelv pine	0.24	m ³	-1.76×10^{-1}	6.43×10^{-1}	-3.83×10^{-2}	[39]
Interior wall							
Structural timber. walls	Spruce C24	2.65	m ³	-5.92×10^2	6.79×10^2	-1.65×10^2	[34]
Insulation	Glava glaswool	116.43	m ²	2.47×10^{-1}	2.29×10^{-3}	-8.40×10^{-3}	[36]
Interior cladding	Gyproc	361.90	m ²	2.18	1.43×10^{-1}	0	[37]
Painting	Lady pure colour	86.31	kg	3.13	1.32×10^{-2}	0	[38]
Skirt boards floor/wall	Moelv pine	0.34	m ³	-5.64×10^2	8.34×10^2	-4.26×10^1	[39]
Ceiling skirting	Moelv pine	0.41	m ³	-1.76×10^{-1}	6.43×10^{-1}	-3.83×10^{-2}	[39]

2.2.2. LECA Masonry Walls

The LECA masonry house had exterior walls, as shown in Figure 4 [40], executed with 300 mm sandwich insulated masonry blocks. The exterior surface treatment comprised two 4 mm layers of fibre-reinforced rendering with fibreglass mesh reinforcement between the two layers of rendering. The finishing layer comprised two layers of silicate paint. The

interior surface treatment consisted of plaster covered with one layer of silicate paint. The inner walls were made of uninsulated LECA masonry, where the load-bearing interior walls comprised 200 mm basic blocks and lightweight walls comprised 118 mm wall blocks. The interior surface treatment on each side of the interior walls was an 8 mm layer of plaster and one coat of silicate paint. Table 2 summarises the construction materials and quantities of the LECA walls.

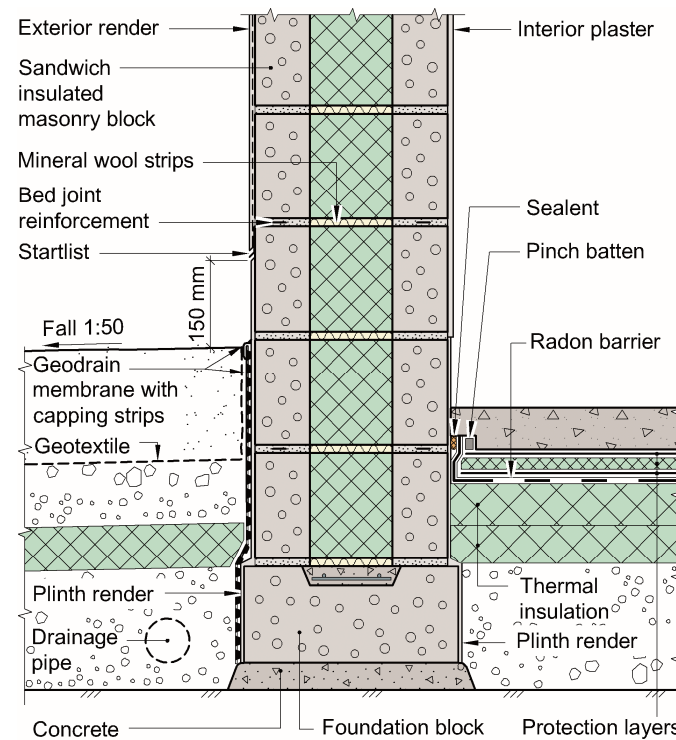


Figure 4. Foundation of LECA masonry exterior wall. Illustration: SINTEF Community.

Table 2. Construction materials for LECA masonry walls.

Building Element	Product	Quantity	Declared Unit (DU)	kg CO _{2eq} /Unit (A1–A5)	kg CO _{2eq} /Unit (C1–C4)	kg CO _{2eq} /Unit (D)	Ref. (EPD)
Exterior wall							
Foundation	Leca foundation block	2.25	m ³	2.71×10^2	0	0	[41]
Exterior wall	Leca isoblokk 300 mm	72.66	m ³	1.47×10^2	0	0	[42]
Exterior render	Weberbase 261	3114.00	kg	2.90×10^{-1}	0	0	[43]
Exterior paints	Silicate Exterior Paints	1557.00	kg	2.39	0	-1.84×10^{-2}	[44]
Interior plaster	Weberbase 132	4152.00	kg	2.04×10^{-1}	9.26×10^{-3}	-3.57×10^{-3}	[45]
Skirt boards floor/wall	Moelv pine	0.21	m ³	-5.64×10^2	8.34×10^2	-4.26×10^1	[39]
Ceiling skirting	Moelv pine	0.24	m ³	-1.76×10^{-1}	6.43×10^{-1}	-3.83×10^{-2}	[39]
Interior wall							
Inner wall	Leca Basicblokk 200 mm	4.06	m ³	1.61×10^2	1.27×10^1	−1.49	[46]
Inner wall	Leca lightweight wall block	14.21	m ³	1.80×10^2	0	0	[47]
Interior plaster	Weberbase KC 50/50	4052.16	kg	1.65×10^{-1}	0	0	[48]
Interior paints	Silicate Exterior Paints	703.50	kg	2.39	0	-1.84×10^{-2}	[44]
Skirt boards floor/wall	Moelv pine	0.34	m ³	-5.64×10^2	8.34×10^2	-4.26×10^1	[39]
Ceiling skirting	Moelv pine	0.41	m ³	-1.76×10^{-1}	6.43×10^{-1}	-3.83×10^{-2}	[39]

2.2.3. Walls of Concrete-Moulded EPS Boards

The exterior walls of the concrete-moulded EPS boards are shown in Figure 5. The interior cladding comprised painted gypsum boards. The inner walls were identical to those of the timber-frame house. Table 3 summarises the construction materials and quantities for the walls of the concrete-moulded EPS boards and the inner walls of the timber frame.

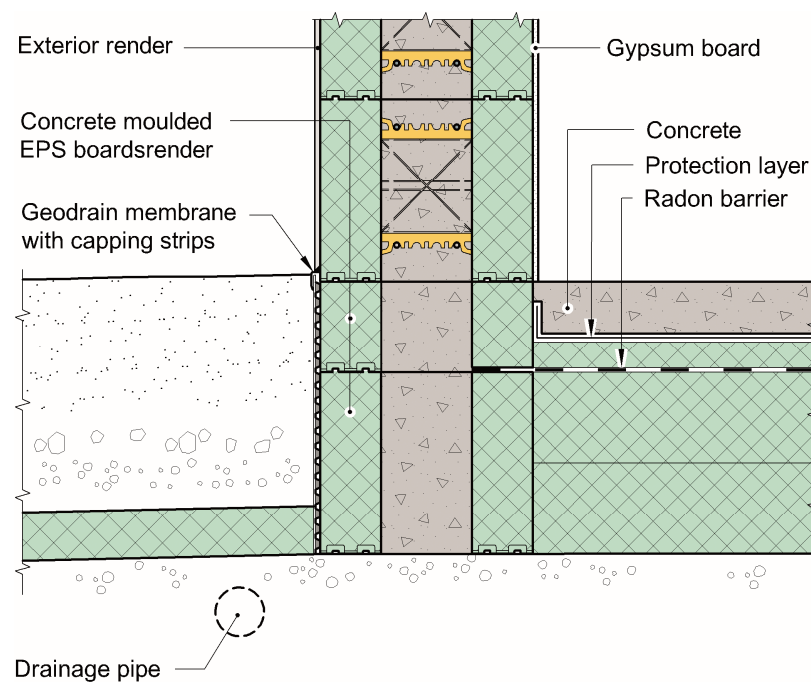


Figure 5. Foundation of exterior walls of concrete-moulded EPS boards. Illustration: SINTEF Community.

Table 3. Construction materials for concrete-moulded EPS boards walls and interior timber-frame walls.

Building Element	Product	Quantity	Declared Unit (DU)	kg CO _{2eq.} /Unit (A1–A5)	kg CO _{2eq.} /Unit (C1–C4)	kg CO _{2eq.} /Unit (D)	Ref. (EPD)
Exterior wall							
Exterior wall	Thermomur	207.60	m ²	2.65×10^1	1.66×10^{-1}	-1.25×10^{-2}	[49]
Interior cladding	Gyproc	198.00	m ²	2.18	1.43×10^{-1}	0	[37]
Interior wall							
Structural timber. walls	Spruce C24	2.65	m ³	-5.92×10^2	1.79×10^2	-1.65×10^2	[33]
Insulation	Glava glaswool	116.43	m ²	2.47×10^{-1}	2.29×10^{-3}	-8.40×10^{-3}	[36]
Interior cladding	Gyproc	361.90	m ²	2.18	1.43×10^{-1}	0	[37]
Painting	Lady pure colour	86.31	kg	3.13	1.32×10^{-2}	0	[38]
Skirt boards floor/wall	Moelv pine	0.34	m ³	-5.64×10^2	8.34×10^2	-4.26×10^1	[39]
Ceiling skirting	Moelv pine	0.41	m ³	-1.76×10^{-1}	6.43×10^{-1}	-3.83×10^{-2}	[39]

2.3. Flooding Case and Rehabilitation

2.3.1. Flooding Damage and Drying

All three houses were exposed to imaginary flooding caused by torrential rain resulting in 50 mm water on the ground floor for seven days. According to a specialist on water and flooding damage from Polygon AS, this is a typical flooding situation caused by torrential rain, see Figure 6. The rehabilitation of water-damaged areas includes drying and reconstruction. The drying of the constructions was conducted according to the recommendations provided by Polygon using fans and a dehumidifier. The electrical consumption of the dehumidifier and fans were 1.2 and 0.1 kW, respectively. Using the GWP of a Nordic electricity mix of 0.136 kg CO_{2eq.}/kWh [50], the GWP of the dehumidifier and fans were calculated. In all three cases, the ground floor and walls were dried. The quantity of materials that must be changed depends on the construction system. This is because certain materials are more waterproof than others. The time required for the construction to dry adequately was provided by the same specialist for water and flooding damage from Polygon.

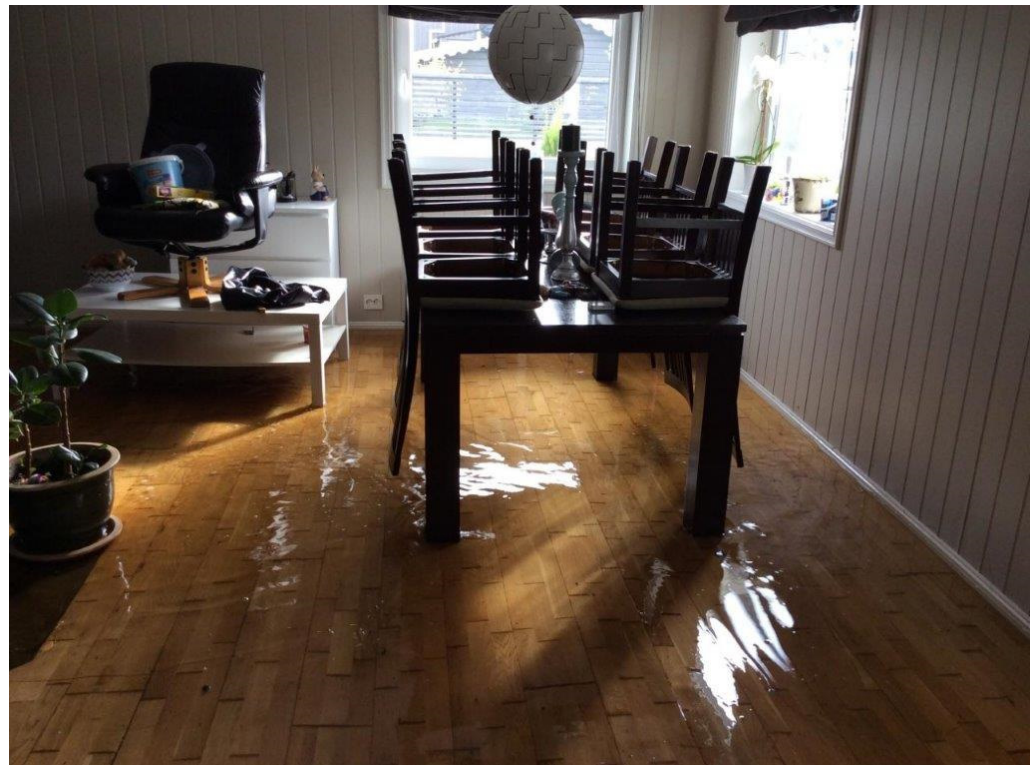


Figure 6. The typical flooding situation caused by torrential rain calculated in this study.

The following sections describe the drying of the construction and the quantity of materials required for reconstruction. The GWP for phases A, C, D, and the EPDs are provided for different materials. The rehabilitation steps applied for all houses are illustrated in Figure 7.

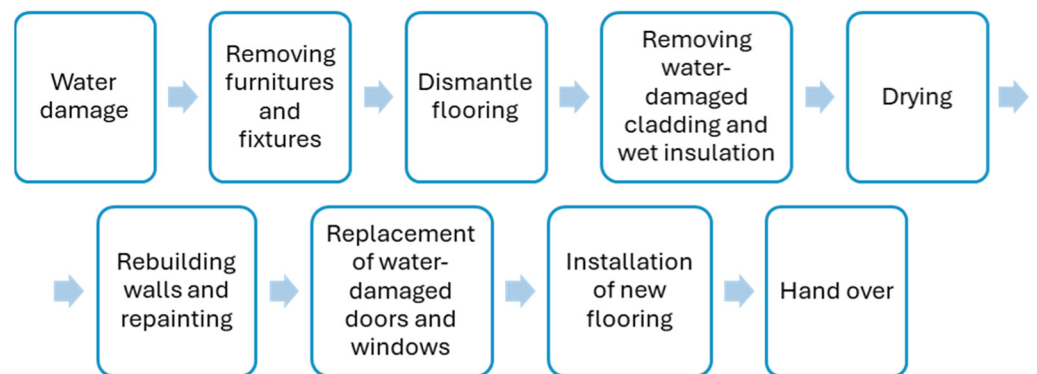


Figure 7. The rehabilitation steps for the water-damaged houses.

2.3.2. Common for All the Houses

The ground level of the houses had two windows down to the ground, a patio door, an exterior door, and four interior doors. All these were replaced, including the frames; however, the fittings (pan flashings) were not. All exterior and interior walls on the ground floor must be painted after being sufficiently dried because flooding can cause miscolouring and efflorescence of salts on the walls. The bathroom had wall panels that had to be removed during the drying of the exterior walls and reinstalled with a new sealant when the walls behind were sufficiently dry. The wall panels on the interior walls of the bathroom were not removed; however, the walls were dried from the other side.

The flooring of each house was identical. The adequate drying of a concrete floor when applying a sealed surface coating depends on the type of flooring [22]. The house had both oak laminate flooring and ceramic tiles from Marazzi. It is possible to dry the floor without removing the ceramic tiles; however, the laminate flooring must be removed and replaced because of moisture exposure. According to a water and flooding damage specialist from Polygon, the concrete floor reached sufficient dryness before the exterior walls. Hence, the drying time for exterior walls was applicable.

Table 4 lists the construction materials for all three houses that must be replaced or renewed.

Table 4. Materials for reconstruction of the three houses.

Building Element	Product	Quantity	Declared Unit (DU)	kg CO _{2eq} /Unit (A1–A5)	kg CO _{2eq} /Unit (C1–C4)	kg CO _{2eq} /Unit (D)	Ref. (EPD)
Exterior wall							
Windows	Nordvestvinduet fixed frame	1.26	pcs	8.28×10^1	3.22×10^1	−8.13	[51]
Framing windows	Moelv pine	0.03	m ³	-5.64×10^2	8.34×10^2	-4.26×10^1	[39]
Patio door with framing	Norgesvinduet two-winged door	2.53	pcs	1.85×10^2	5.74×10^1	-4.33×10^1	[52]
Exterior door with framing	Nordan	1.57	pcs	6.21×10^1	8.50×10^1	−4.80	[53]
Skirt boards door threshold	Moelv pine	3.33	m	-1.76×10^{-1}	6.43×10^{-1}	-3.83×10^{-2}	[54]
Skirting for doors and windows	Moelv pine	0.01	m ³	-5.64×10^2	8.34×10^2	-4.26×10^1	[39]
Frame screws	Cold-rolled stainless-steel	2.38	kg	2.05	8.33×10^{-2}	−1.52	[55]
Surface finishing	Lady pure colour	18.90	kg	3.13	1.32×10^{-2}	0	[38]
Skirt boards floor/wall	Moelv pine	0.10	m ³	-5.64×10^2	8.34×10^2	-4.26×10^1	[39]
Sealant for bathroom panels	Tec7	0.17	kg	5.02	2.22	-9.50×10^{-1}	[56]
Interior wall							
Interior doors	Harmonie	3.37	pcs	−5.04	8.34×10^1	−3.17	[57]
Framing doors	Moelv pine	0.02	m ³	-5.64×10^2	8.34×10^2	-4.26×10^1	[39]
Skirting doors	Moelv pine	0.03	m ³	-5.64×10^2	8.34×10^2	-4.26×10^1	[39]
Skirt boards door threshold	Moelv pine	8.44	M	-1.76×10^{-1}	6.43×10^{-1}	-3.83×10^{-2}	[54]
Frame screws	Cold-rolled stainless-steel	8.77	kg	2.05	8.33×10^{-2}	−1.52	[55]
Surface finishing	Lady pure colour	25.20	kg	3.13	1.32×10^{-2}	0	[38]
Skirt boards floor/wall	Moelv pine	0.04	m ³	-5.64×10^2	8.34×10^2	-4.26×10^1	[39]
Floorings							
Flooring	OPUS 1-strip laminate oak light	74	m ²	2.79	1.74	8.70×10^{-1}	[58]
Underlay for flooring	Hunton Silencio	74	m ²	-5.32×10^{-1}	5.27	-3.65×10^{-1}	[59]
Pin	Cold-rolled stainless-steel	0.12	kg	2.05	8.33×10^{-2}	−1.52	[55]

2.3.3. Rehabilitation of Timber-Frame Walls

In timber-frame walls, timber is commonly dried by opening the exterior wall from the interior [20]. To dry the timber-frame walls, the dehumidifier and fan must run for 42 days (1008 h, equivalent to 1210 and 101 kWh, respectively). To ensure that the timber studs were sufficiently dry, the moisture was measured in the lower part of the bottom sill, where the moisture levels were usually the highest [20].

Three hundred millimetres of gypsum and insulation on all exterior and interior walls were replaced with new materials, because microbial growth can occur if gypsum and insulation are exposed to moisture for extended periods [60]. A water-damage specialist recommended a distance of 300 mm. In addition, 300 mm of the vapour barrier in the external wall must be replaced to dry the construction. Table 5 lists materials that must be replaced or renewed.

Table 5. Materials for reconstruction of the timber-frame house.

Building Element	Product	Quantity	Declared Unit (DU)	kg CO _{2eq} /Unit (A1–A5)	kg CO _{2eq} /Unit (C1–C4)	kg CO _{2eq} /Unit (D)	Ref. (EPD)
Exterior wall							
Interior cladding	Gyproc	6.63	m ²	2.18	1.43×10^{-1}	0	[37]
Joint compound for gypsum board	Jotun	2.64	kg	6.80×10^{-1}	0	0	[61]
Vapour barrier	Baca vapour barrier	27.38	m ²	5.44×10^{-1}	0	0	[35]
Pin	Cold-rolled stainless-steel	0.03	kg	2.05	8.33×10^{-2}	−1.52	[55]
Tape		2.25					
Insulation	Glava glaswool	53.35	m ²	2.47×10^{-1}	2.29×10^{-3}	-8.40×10^{-3}	[36]
Gypsum screw	Cold-rolled stainless-steel	0.32	kg	2.05	8.33×10^{-2}	−1.52	[55]
Interior wall							
Interior cladding	Gyproc	13.3	m ²	2.18	1.43×10^{-1}	0.00	[37]
Joint compound for gypsum board	Jotun		kg	6.80×10^{-1}	0	0	[61]
Insulation	Glava glaswool	11.28	m ²	2.47×10^{-1}	2.29×10^{-3}	-8.40×10^{-3}	[36]
Gypsum screw	Cold-rolled stainless-steel	0.85	kg	2.05	8.33×10^{-2}	−1.52	[55]

2.3.4. Rehabilitation of LECA Masonry Walls

To dry LECA masonry walls, the dehumidifier and fans must run for 6 months/1260 days/30,240 h to achieve sufficient dryness. This represents 36,288 and 3024 kWh for the dehumidifier and fans, respectively. The walls of the ground floor were painted after drying. For the LECA masonry, most of the materials were dried, and there was no extra material, except for the common material that was replaced for all three houses.

2.3.5. Rehabilitation of Walls of Concrete-Moulded EPS Boards

To dry the house composed of concrete-moulded EPS boards, the dehumidifier and fans must run for 42 days (1008 h), which is equivalent to 1210 and 101 kWh, respectively. Owing to the flooding, 300 mm of gypsum boards were replaced on the exterior and interior walls, and all the walls were painted. In addition, 300 mm of insulation was replaced on the inner wall. Table 6 lists materials that must be replaced or renewed.

Table 6. Materials for reconstruction of concrete-moulded EPS boards house.

Building Element	Product	Quantity	Declared Unit (DU)	kg CO _{2eq} /Unit (A1–A5)	kg CO _{2eq} /Unit (C1–C4)	kg CO _{2eq} /Unit (D)	Ref. (EPD)
Exterior wall							
Interior cladding	Gyproc	6.63	m ²	2.18	1.43×10^{-1}	0	[37]
Joint compound for gypsum board	Jotun	2.64	kg	6.80×10^{-1}	0	0	[61]
Interior wall							
Interior cladding	Gyproc	13.3	m ²	2.18	1.43×10^{-1}	0	[37]
Joint compound for gypsum board	Jotun		kg	6.80×10^{-1}	0	0	[61]
Insulation	Glava glaswool	11.28	m ²	2.47×10^{-1}	2.29×10^{-3}	-8.40×10^{-3}	[36]
Gypsum screw	Cold-rolled stainless-steel	0.85	kg	2.05	8.33×10^{-2}	−1.52	[55]

2.4. Joint Workshops with Experts

A group of experts in the field of construction engineering from SINTEF gathered in a workshop to validate the suggested solutions for flooding damage drying and rehabilitation. In addition, the group validated the redesign from the timber-frame house to the LECA masonry and concrete-moulded EPS board houses. The workshop participants included the authors, an expert in timber frame buildings (a carpenter and engineer with 18 years of experience), an expert in the design of masonry (mason and M.Sc. with 19 years of experience), and a generalist in the field of construction engineering (bachelor's degree

with 35 years of experience). The workshop began with an introduction to this study's aim, suggested methods, and solutions. Subsequently, the participants provided feedback and suggestions. The expert workshop did not discuss about LCA.

3. Results

The GWP of the construction materials for the three houses with different construction methods and for the rehabilitation of flooding are presented in Table 7.

Table 7. GWP of the three houses.

	1: Timber Frame	2: LECA Masonry	3: Concrete-Moulded EPS Boards
GWP of original building materials [kg CO _{2eq.}]	2.70×10^4	4.24×10^4	3.11×10^4
GWP of drying [kg CO _{2eq.}]	1.78×10^2	5.35×10^3	1.78×10^2
GWP for reconstruction [kg CO _{2eq.}]	2.31×10^3	2.21×10^3	2.27×10^3
Total GWP [kg CO _{2eq.}]	2.95×10^4	5.00×10^4	3.35×10^4

For the timber-frame house, the reconstruction materials accounted for 8% of the original construction material, whereas the drying accounted for 1%. For the LECA masonry house, the material replacement accounted for 4% of the construction material. However, the drying accounted for as much as 11%. Further, replacement of materials for the concrete-moulded EPS board houses accounted for 7% of the construction materials and drying accounted for 1%. The overall GWP for construction of the timber-frame house and rehabilitation after flooding accounted for 88% and 59% of the concrete and LECA masonry houses, respectively.

4. Discussion

4.1. Construction Methods

Building elements contribute differently to the GWP depending on the construction method used, as shown in Figure 8. The foundation and fundamentals account for the greatest share of the GWP of the timber-frame house, whereas, for the concrete and LECA masonry houses, the exterior walls required the greatest measure. For the LECA masonry house, the exterior walls contributed as much as 48% of the total GWP. However, the EPD for the LECA sandwich-insulated masonry and LECA wall blocks for the non-bearing inner walls did not include phases C and D, which rendered the comparability of these houses doubtful. The difference in the EPD information provided rendered it difficult to compare construction methods. This was also confirmed in [62].

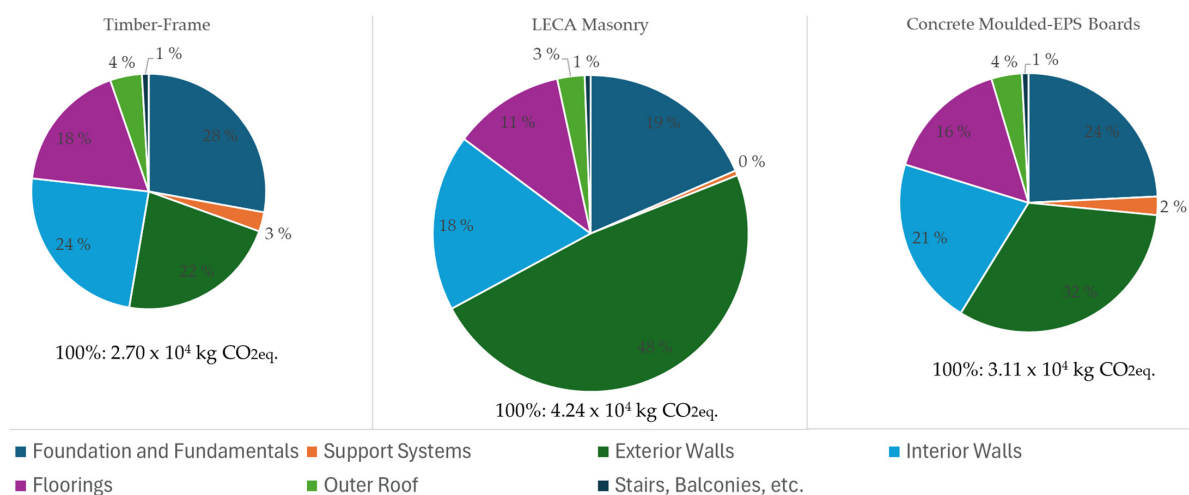


Figure 8. GWP per building element for the three construction methods.

4.2. Rehabilitation of Water Damages Caused by Flooding

Flooding to the LECA masonry house generated few reconstruction materials; however, the drying time for the LECA masonry blocks was very long compared to the two other houses. Hence, drying significantly contributed to the overall GWP. In contrast, for timber frames and concrete houses, the drying of materials had a minimal impact on the overall GWP compared with the replacement of materials. For these two construction methods, drying as much material as possible is important for reducing the overall GWP. Figure 9 shows the distribution of the contributing building elements for the reconstruction of water-damaged timber-frame houses.

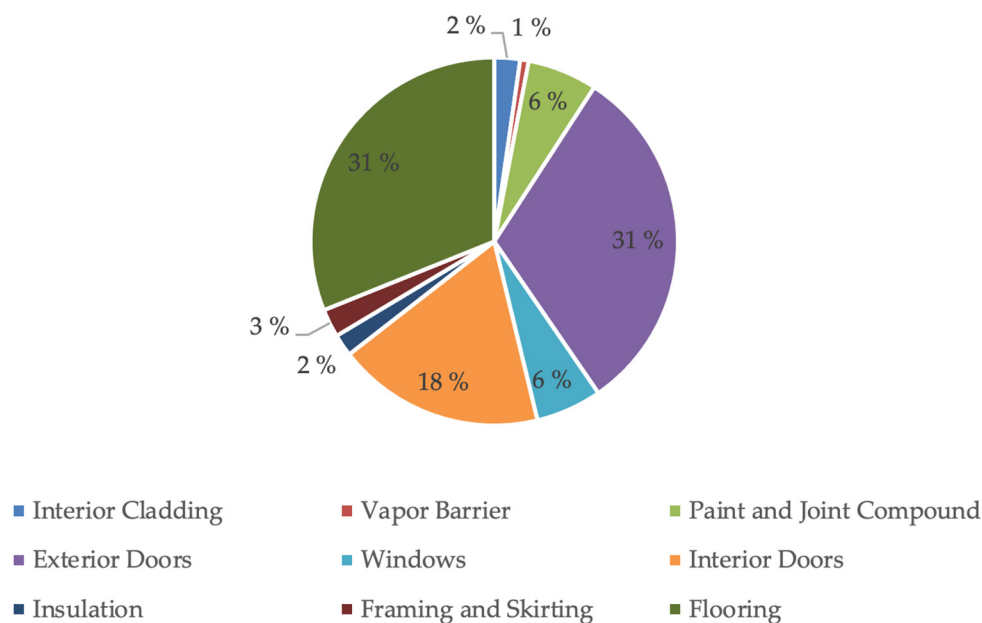


Figure 9. Distribution of GWP for reconstruction after flooding in timber-frame house.

The exterior doors, flooring, and interior doors had the largest GWP contributions from the reconstruction materials. To reduce the GWP of reconstructed materials, materials that can be dried must be used. It is possible to choose more water-resistant materials such that fewer materials need to be changed when exposed to water [60].

According to Figure 9, the replacement of exterior and interior doors has a significant impact on the total GWP. The exterior and interior doors contribute 7.25×10^2 and 4.25×10^2 kg CO_{2eq.}, respectively. [60] recommended the use of internal doors that can be dried, such as solid timber doors with a high-build paint system and hinges that facilitated the removal of the door for drying during floods. The interior doors normally used by Norgeshus comprised a core with a paper honeycomb that is not resistant to water exposure. Furthermore, [60] recommended using PVC-U doors as exterior doors because they are water resistant. The exterior doors used by Norgeshus for this house model were composed of high-density fibreboard, which swelled when exposed to water for an extended period. The patio doors used in the house comprised pine veneers, which also swelled when exposed to water. Drying all the doors could reduce the GWP by 1.14×10^3 kg CO_{2eq.}, which is 49% of the reconstruction GWP.

The replacement of laminate flooring contributes 7.22×10^2 kg CO_{2eq.}. By using ceramic tiles in the ground floor instead of laminate flooring, the total GWP for construction and rehabilitation will decrease by 2.96×10^2 kg CO_{2eq.}. Hence, if future flooding is suspected, ceramic tiles are a favourable flooring material with regard to GWP because they can be dried and do not need to be replaced.

The original timber-frame house used glass wool as insulation, but this type of insulation sinks when wet. Compaction of the insulation may slow the drying of the cavity [58]. An alternative material with good resistance to floodwater is a closed-cell insulation board,

such as Extruded Polystyrene (XPS). This is because this type of insulation can be dried if properly fixed and does not move when exposed to floods. However, changing the insulation to XPS will result in a considerably greater construction GWP, and only 2% GWP reduction in reconstruction. Changing to XPS will not reduce total GWP. Additionally, XPS exhibits poor fire resistance and limited sound insulation [63].

4.3. Potential Carbon Footprint of Flooding Due to Torrential Rain in Norway

The carbon footprint of the rehabilitation of flooding owing to extreme weather is not included in the total carbon footprint of a house, although it has a significant GWP. To the best of our knowledge, there have been no studies on the contribution of extreme weather to GWP damage. Assuming that all the 13,800 damaged houses from the recent Norwegian torrential rain event 'Hans' (August 2023) had the same carbon footprint as the flooding on the timber-frame house described in this study, the carbon footprint of 'Hans' would be 3.49×10^7 kg CO_{2eq.}. With the assumption that torrential rain events like 'Hans' will happen more frequently in the future [15], an increment in flooding and consequently the carbon footprint of buildings is expected.

Since 2010, there have been six large natural events in addition to 'Hans', with a total of 55,567 insurance claims [17]. With the same assumptions as for 'Hans', the carbon footprint of extreme weather in Norway the last 10 years has the potential to reach 1.38×10^8 kg CO_{2eq.}, which is the same as constructing 5120 timber-frame houses. By comparison, a total of 4497 single-family residential buildings were constructed in Norway in 2023 [64]. Only three large natural events were recorded from 1980 to 2010 [17], indicating that these events have occurred more frequently in the last 10 years. Although there are several ways to reduce the carbon footprint of flooding, industries should focus on reducing global emissions to counteract global warming and, as a result, reduce the frequency and intensity of extreme weather events.

The flooding described in this study is representative of the flooding caused by torrential rain; however, rain episodes such as this also result in both smaller and more complex floodings. An estimation of the GWP, as presented, provides an indication of the significance of flooding which must be considered when constructing buildings. Therefore, more robust solutions are required to reduce carbon footprints as well as development of more efficient drying procedures.

5. Conclusions

Constructing a typical modern Norwegian detached timber-frame house results in a carbon footprint of 2.70×10^4 kg CO_{2eq.}, whereas the impact of the same house model constructed with LECA masonry and using the exterior walls of concrete-moulded EPD boards is 4.24×10^4 kg CO_{2eq.} and 3.11×10^4 kg CO_{2eq.}, respectively.

Exposed to a typical flooding situation caused by torrential rain with five centimetres water on the ground floor for seven days, the rehabilitation from flooding within the three houses represents a significant carbon footprint. The incident yielded 2.49×10^3 CO_{2eq.} for the timber-frame house, 7.56×10^3 CO_{2eq.} for the LECA masonry house, and 2.45×10^3 CO_{2eq.} for the concrete-moulded EPD board house. It is difficult to conclude whether one construction method is better than the others, owing to the poor comparability of EPDs. This study indicates that timber-frame houses have a lower carbon footprint when exposed to flooding, although wood is more moisture sensitive than LECA masonry and concrete. This is because the carbon footprint of constructing a timber-frame house is far lower than that of LECA and concrete. Moreover, the carbon footprint of rehabilitation does not significantly outweigh this although more materials need to be replaced in a timber-frame house. The carbon footprint of rehabilitating flooding can be reduced if water-resistant materials that can be dried are used, such as internal doors of solid timber with a high-build paint system.

An increase in torrential rain significantly increases the extent of flooding, and consequently increases the carbon footprint of buildings. This study found that the potential carbon footprint of extreme weather events over the last 10 years was 1.38×10^8 kg CO_{2eq.},

which indicates that flooding is responsible for significant emissions. It is important to make appropriate material choices and design robust solutions to reduce the overall carbon footprint of extreme weather events; however, the most crucial aspect is to counteract global warming, thereby reducing extreme weather events.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/buildings14071967/s1>, File S1: Timber-frame carbon footprint construction; File S2: Timber-frame carbon footprint reconstruction; File S3: LECA carbon footprint construction; File S4: LECA carbon footprint reconstruction; File S5: Concrete carbon footprint construction; File S6: Concrete carbon footprint reconstruction.

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