Supporting Information

Strategies to Improve the Energy Performance of Buildings: A Review of Their Life Cycle Impact

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S1. METHODOLOGY

After selecting the final sample of papers, the project team developed a matrix (see separate Excel file dating from 31 July 2017) in which the main findings from the different literature studies could be summarised. It resembles a data extraction form, containing all information perceived relevant, in an attempt to provide a combined quantitative and qualitative analysis of the scientific state-of-the-art. The different literature studies are presented in a matrix table indicating:

- Which research questions are answered by the document;
- File name;
- Title of the document;
- The authors;
- Solution category for energy efficiency improvements:
  - insulation and improvement of the envelope;
  - replacement of the equipment;
  - on-site installations for renewable energy;
  - automation of the building;
  - etc.
- Short description of the solution presented in the document;
- Source of or link to the document;
- Name of journal/paper;
- Country covered within the document;
- Publication year of the document;
- Building typology covered by the document;
- Whether it covers new build or refurbishment case(s);
- Typology of the energy performance;
- System boundaries of the LCA;
- Important assumptions in the study (e.g. allocation);
- Additional comments related to the LCA modelling;
- Database used for the LCA modelling;
- Reference study period;

- Whether it is a qualitative or quantitative study;
- Additional comments on the document;
- Construction method of the covered case(s);
- Thermal insulation material used;
- Which parts of the building was included in the LCA;
- Applied assessment methodology;
- LCA software used;
- Indicators assessed;
- Gross floor area [m²];
- Net floor area [m²];
- Reference area for EE/EC [m²];
- Final operational energy demand [kWh/m²a];
- Final energy demand for electricity [kWh/m²a];
- Final energy demand for heating and hot water [kWh/m²a];
- Final energy demand for cooling [kWh/m²a];
- Climate change impacts for each stage of the building's life cycle, according to EN 15978 (from Modules A to D);
- Primary energy (non-renewable) consumption for each stage of the building's life cycle, according to EN 15978 (from Modules A to D);
- Abiotic Depletion Potential impacts for each stage of the building's life cycle, according to EN 15978 (from Modules A to D);
- Hazardous waste generation for each stage of the building's life cycle, according to EN 15978 (from Modules A to D);
- Single environmental score for each stage of the building's life cycle, according to EN 15978 (from Modules A to D);
- Fifteen columns show results calculated by the embedded formulae within the matrix, to portray each life cycle stage contribution to the assessed building's total load;
- Fifteen columns regarding the ratio of impacts caused by insulation and one column regarding the tipping point of insulation, followed the same number and type of columns but for renewable energy installations;
- And, finally, last ten columns include information regarding the financial cost.

S2. RESULTS

S2.1 General overview, meta- analysis

Number of papers reviewed

- 59 papers;
- 5 different scientific journals;
- 16 "others" = 1 EPD, 1 magazine article, 2 conference proceedings, 1 PhD thesis. 3 research reports, and 7 case studies.

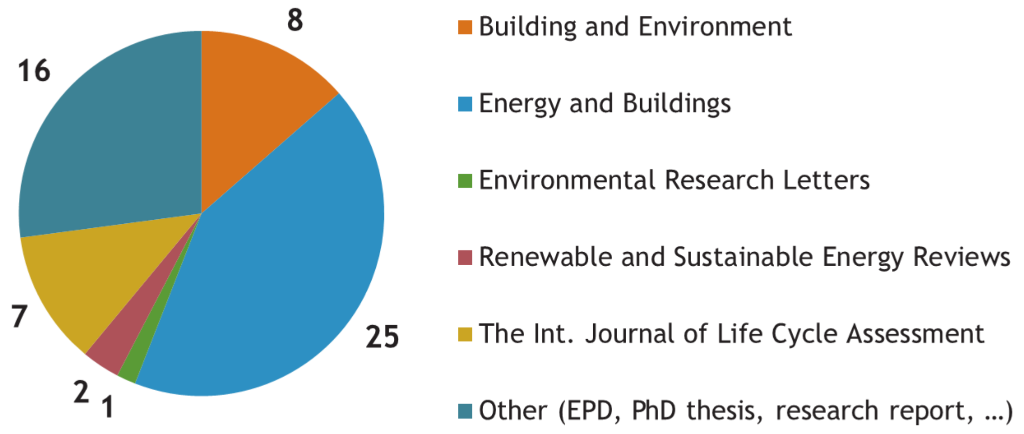

Figure S1: Number and types of papers reviewed

- The 178 case studies covered 18 different countries:

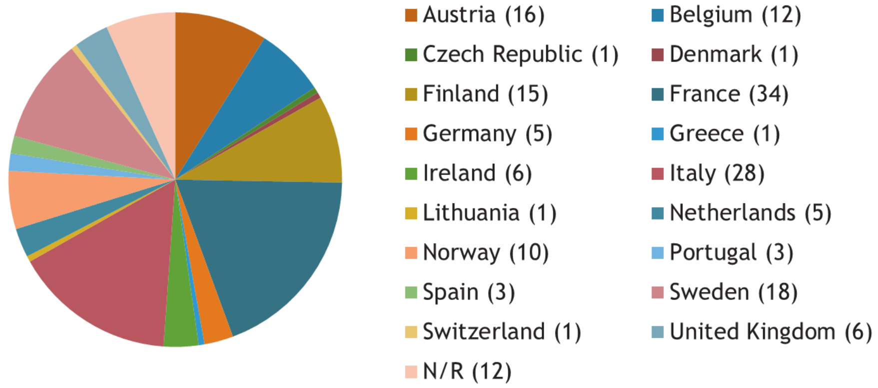

Figure S2: Number of countries covered by the case studies.
(N/R = not relevant/ review paper/ multiple countries)

- The energy performance level was given from 135 out of 178 case studies, and those 135 cases covered 7 types of energy performance level:

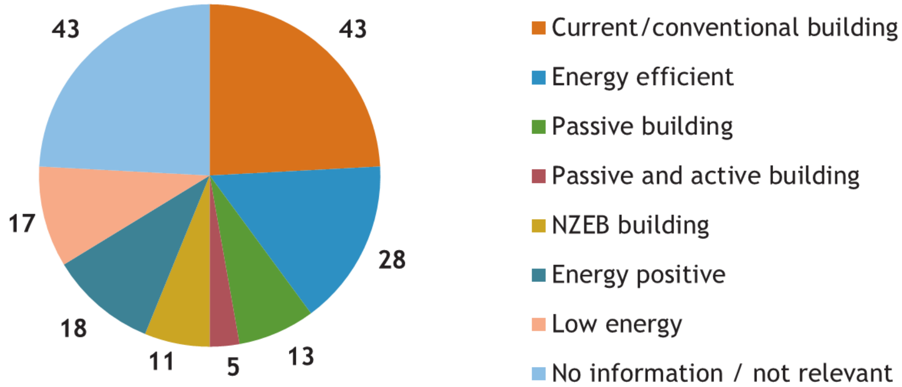

Figure S3: Types of energy performance levels covered by the case studies

- The 178 case studies covered 111 new built cases and 41 refurbishment cases:

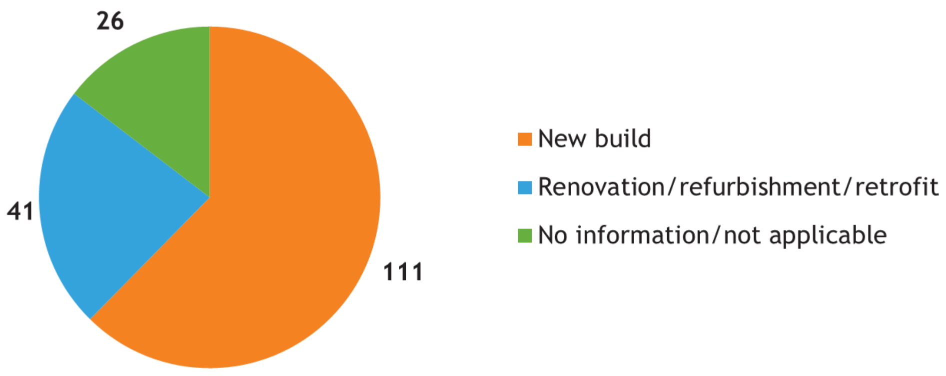

Figure S4: Division of new built – renovation case studies

- 172 out of 178 case studies covered 6 different system boundaries:

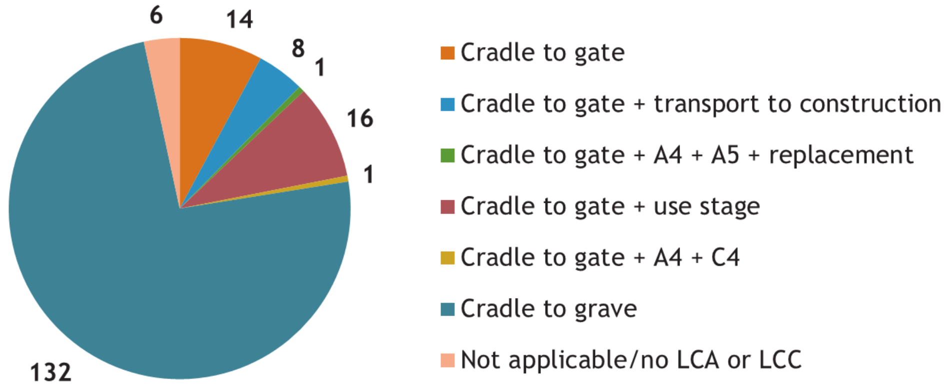

Figure S5: Types of system boundaries covered by the case studies

S2.2 Research Question 1 – RQ1

The presented ratios are results calculated with the matrix based on absolute figures taken from the papers or visually extrapolated from graphs within the papers. The project team divided the impact with a 95%-5% division for the cases where figures were given for the complete module A (i.e. production stage including construction stage, thus attributing 95% to the production stage and 5% to the construction stage). For a complete overview, e.g. for other impact categories or incomplete figures of other cases, please refer to the matrix.

Table S1: Life cycle impact assessment of three stone wool insulation thicknesses: 40, 80 and 120 mm (functional unit of 1 m^2 of living area over a period of 50 years) [22]

	No insulation		RW40		RW80		RW120		No insulation		RW40		RW80		RW120	
	Climate change (kg CO_2 eq)								**Primary energy (MJ)**							
Removal	4.3	(2%)	4.3	(2%)	4.3	(2%)	4.3	(2%)	33	(1%)	33	(1%)	33	(1%)	33	(1%)
Construction	50	(21%)	59	(28%)	69	(32%)	78	(36%)	846	(24%)	1035	(32%)	1201	(37%)	1357	(41%)
Operational Energy	160	(69%)	130	(61%)	120	(57%)	115	(53%)	2277	(65%)	1843	(57%)	1705	(52%)	1626	(49%)
Maintenance	19	(8%)	19	(9%)	19	(9%)	19	(9%)	324	(9%)	324	(10%)	324	(10%)	324	(10%)
Total	233		212		211		215		3479		3235		3263		3340	
	Terrestrial acidification (kg SO_2 eq)								**Ozone depletion (mg CFC-11 eq)**							
Removal	0.02	(1%)	0.02	(1%)	0.02	(1%)	0.02	(1%)	0.3	(2%)	0.3	(2%)	0.3	(2%)	0.3	(2%)
Construction	0.23	(14%)	0.28	(20%)	0.34	(24%)	0.39	(28%)	4.9	(27%)	5.7	(34%)	6.4	(38%)	7.1	(41%)
Operational Energy	1.29	(79%)	1.04	(73%)	0.96	(68%)	0.92	(65%)	10.4	(58%)	8.4	(50%)	7.8	(46%)	7.5	(43%)
Maintenance	0.09	(6%)	0.09	(7%)	0.09	(7%)	0.09	(7%)	2.4	(13%)	2.4	(14%)	2.4	(14%)	2.4	(14%)
Total	1.6		1.44		1.41		1.42		18.1		16.8		16.9		17.3	
	Freshwater eutrophication (kg P eq)								**Marine eutrophication (kg N eq)**							
Removal	0.0004	(0.4%)	0.0004	(0.5%)	0.0004	(1%)	0.0004	(0.5%)	0.001	(3%)	0.001	(3%)	0.001	(3%)	0.001	(3%)
Construction	0.014	(16%)	0.016	(22%)	0.019	(26%)	0.022	(30%)	0.012	(23%)	0.014	(29%)	0.017	(33%)	0.019	(37%)
Operational Energy	0.066	(77%)	0.053	(71%)	0.049	(66%)	0.047	(63%)	0.033	(62%)	0.027	(54%)	0.025	(50%)	0.024	(47%)
Maintenance	0.005	(6%)	0.005	(7%)	0.005	(7%)	0.005	(7%)	0.007	(12%)	0.007	(14%)	0.007	(14%)	0.007	(13%)
Total	0.085		0.075		0.074		0.075		0.054		0.049		0.05		0.05	

S2.2.1 Current/conventional buildings

Table S2: Illustrative examples of the weight of each stage of conventional cases.

Paper	Country covered	Building typology	New build or refubishment?	Reference study period	Construction method	Relative contribution per life cycle stage to the total life cycle impact of the building [%] – Climate change: production stage	Climate change: construction stage	Climate change: use stage	Climate change: end-of-life stage	Primary energy: production stage	Primary energy: construction stage	Primary energy: use stage	Primary energy: end-of-life stage
Dahlstrom et al., 2012	Norway	Residential - single-family or terrassed houses	New build	50 years	Wooden frame house	19.0	1.0	75.0	5.0	9.5	0.5	1.0	89.0
	Norway	Residential - single-family or terrassed houses	New build	50 years	Wooden frame house	20.9	1.1	73.0	5.0	11.4	0.6	1.0	87.0
	Norway	Residential - single-family or terrassed houses	New build	50 years	Wooden frame house	21.9	1.2	69.0	8.0	10.5	0.6	2.0	87.0
	Norway	Residential - single-family or terrassed houses	New build	50 years	Wooden frame house	23.8	1.3	65.0	10.0	12.4	0.7	1.0	86.0
Asdrubali et al., 2013	Italy	Residential - single-family or terrassed houses	New build	50 years	Brick house built in 2002 with thermal insulation in the space, internal plaster, and external plaster and bricks. Aluminum windows. Insulated roof. Reinforced concrete structure. Longitinal axis of building N-S orientated. Gas-fired heating system.	83.3	4.4	4.7	7.6	81.3	4.3	6.3	8.1
	Italy	Residential - multi-apartment buildings	New build	50 years	Brick building with 18 flats built in 2008 with thermal insulation in the space, internal plaster, and external plaster and bricks. Aluminum windows. Flat insulated roof. Reinforced concrete structure. Longitinal axis of building E-W orientated. Gas-fired autonomous heating system per flat.	82.9	4.4	5.6	7.1	80.7	4.2	6.9	8.2
	Italy	Public - Office buildings	New build	50 years	Brick building built in 2009 with thermal insulation in the space, internal plaster, and external claddings. Large-sized aluminum windows. Flat insulated roof. Reinforced concrete structure. Longitinal axis of building N-S orientated. Air-conditioning system with primary air and fan-coils.	77.3	4.1	8.6	10.1	77.9	4.1	10.2	7.8
Weiler et al., 2017 (*)	Germany	Residential - multi-apartment buildings	N/A (No information/ not applicable)	50 years	Honey comb bricks and reinforced concrete	4.6	0.2	94.0	1.1	4.9	0.3	93.9	0.9

(*) In the paper by Weiler *et al.* (2017) one building was analysed on three levels of energy performance (i.e. conventional, passive, and low-energy). During the final meeting there were some questions regarding the comparison of the cases by Weiler; therefore Annex A presents some of the additional results by Weiler *et al.*

S2.2.2 Nearly zero-energy buildings

Table S3: Illustrative example of the weight of each stage of a NZEB case.

Paper	Country covered	Building typology	New build or refubishment?	Reference study period	Construction method	Climate change				Primary energy			
						production stage	construction stage	use stage	end-of-life stage	production stage	construction stage	use stage	end-of-life stage
Paleari et al., 2016	Italy	Residential - multi-apartment buildings	New build	100 years	reinforced concrete load-bearing structures, with lightening brick blocks in the slabs of the residential parts. Perimeter walls of thermal brick blocks with an external insulation in rock wool panels; internal partitions in brick with traditional plaster. Roof structures of glue-laminated wood; pitches insulated through rock wool panels and a multilayer reflective insulation composed of several aluminium sheets alternated with expanded polyethylene layers; finishing pitch surfaces in concrete tiles	55.7	5.8	35.6	2.9	54.7	4.0	39.1	2.2

S2.2.3 PASSIVE HOUSE BUILDINGS

Table S4: Illustrative examples of the weight of each stage of passive house cases.

						Relative contribution per life cycle stage to the total life cycle impact of the building [%]							
						Climate change				Primary energy			
Paper	Country covered	Building typology	New build or refubishment?	Reference study period	Construction method	production stage	construction stage	use stage	end-of-life stage	production stage	construction stage	use stage	end-of-life stage
Proietti et al.,2013 (*)	Italy	Residential - single-family or terrassed houses	New build	70 years	New built passive house Materials: cement, steel, wood, PV HVAC, wood-alu windows	242.1	80.7	-190.9	-31.9	1022.4	255.6	-691.9	-486.1
	Italy	Residential - single-family or terrassed houses	New build	70 years	New built passive house Materials: cement, steel, wood, PV HVAC, wood-alu windows	30.0	10.3	-23.4	83.0	102.6	27.9	-39.2	8.7
	Italy	Residential - single-family or terrassed houses	New build	70 years	New built passive house Materials: cement, steel, wood, PV HVAC, wood-alu windows	40.6	13.9	51.0	-5.5	4829.3	1310.5	-3547.3	-2492.4
Dahlstrom et al., 2012	Norway	Residential - single-family or terrassed houses	New build	50 years	Wooden frame house	28.5	1.5	60.0	10.0	12.4	0.7	86.0	1.0
	Norway	Residential - single-family or terrassed houses	New build	50 years	Wooden frame house	29.5	1.5	57.0	12.0	13.3	0.7	85.0	1.0
	Norway	Residential - single-family or terrassed houses	New build	50 years	Wooden frame house	31.4	1.7	55.0	12.0	15.2	0.8	82.0	2.0
	Norway	Residential - single-family or terrassed houses	New build	50 years	Wooden frame house	31.4	1.7	55.0	12.0	16.2	0.8	82.0	1.0
Weiler et al., 2017 (**)	Germany	Residential - multi-apartment buildings	Renovation / refurbishment / retrofit	50 years	Honey comb bricks and reinforced concrete	13.4	0.7	83.2	2.7	17.1	0.9	80.0	2,0

(*) The negative values (i.e. benefits) in the use stage is explained by the presentence of a 6 kWp PV system, which produces more energy than the house consumes. The negative values in the end-of-life stage is explained by the assumed recycling/reusing processes. This paper does not apply the methodology of the EN 15804 and therefore includes the net benefits in the different stages instead of declaring them in a separate Module D.

(**) In the paper by Weiler *et al.* (2017) one building was analysed on three levels of energy performance (i.e. conventional, passive, and low-energy). During the final meeting there were some questions regarding the comparison of the cases by Weiler; therefore Annex A presents some of the additional results by Weiler *et al.* .

S2.2.4 ENERGY POSITIVE BUILDINGS

Table S5: Illustrative examples of the weight of each stage of energy positive cases.

						Relative contribution per life cycle stage to the total life cycle impact of the building [%]							
						Climate change				Primary energy			
Paper	**Country covered**	**Building typology**	**New build or refubishment?**	**Reference study period**	**Construction method**	**production stage**	**construction stage**	**use stage**	**end-of-life stage**	**production stage**	**construction stage**	**use stage**	**end-of-life stage**
Thiers and Peuportier, 2012	France	Residential - single-family or terrassed houses	New build	N/A (built in 2007)	No information	42.6	2.1	34.0	21.3	89.0	4.5	4.3	2.2
	France	Residential - single-family or terrassed houses	New build	N/A (built in 2007)	No information	46.5	2.3	27.9	23.3	87.3	4.4	6.2	2.1
	France	Residential - single-family or terrassed houses	New build	N/A (built in 2007)	No information	46.5	2.3	27.9	23.3	79.0	4.0	15.5	1.5
	France	Residential - multi-apartment buildings	Renovation / refurbishment / retrofit	N/A (renovated in 2001)	No information	29.0	1.4	63.8	5.8	8.9	0.4	89.5	1.1
	France	Residential - multi-apartment buildings	Renovation / refurbishment / retrofit	N/A (renovated in 2001)	No information	32.8	1.6	59.0	6.6	9.8	0.5	88.5	1.2
	France	Residential - multi-apartment buildings	Renovation / refurbishment / retrofit	N/A (renovated in 2001)	No information	19.8	1.0	75.2	4.0	11.2	0.6	86.8	1.4

S2.2.5 Low energy buildings

Table S6: Illustrative examples of the weight of each stage of low energy cases.

Paper	Country covered	Building typology	New build or refubishment?	Reference study period	Construction method	Relative contribution per life cycle stage to the total life cycle impact of the building [%]							
						Climate change				Primary energy			
						production stage	construction stage	use stage	end-of-life stage	production stage	construction stage	use stage	end-of-life stage
Blengini & Di Carlo, 2010	Italy	Residential - single-family or terrassed houses	New build	N/A	Designed according to sustainable and bioclimatic architecture principles	56.5	3.0	45.9	-5.4	51.4	2.7	35.1	10.8
Weiler et al., 2017 (*)	Germany	Residential - multi-apartment buildings	New build	50 years	Reinforced concrete frame	11.9	0.6	85.1	2.4	11.9	0.6	85.5	2.0

(*) In the paper by Weiler *et al.* (2017) one building was analysed on three levels of energy performance (i.e. conventional, passive, and low-energy). During the final meeting there were some questions regarding the comparison of the cases by Weiler; therefore Annex A presents some of the additional results by Weiler *et al.* .

S3 ADDITIONAL STUDIES REVIEWED

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